Assessment of the State-of-the-Art of Remote Irrigation Control Systems

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ABSTRACT

California State University, Chico conducted a research project for the California Department of Transportation (Caltrans) to develop a state-of-the-art assessment of Remote Irrigation Control (RIC) systems that may used for highway right-of-way irrigation. The primary goal of the study was to provide Caltrans maintenance personnel with a central reference source on Remote Irrigation Control. The research includes: a survey of fourteen current RIC systems, an analysis of communication methods used in RIC systems, a survey of current RIC expertise at Caltrans, and an examination of future trends and technologies. A generic remote irrigation control system model and a set of benchmark features were developed to aid in system comparison. The use of environmental feedback in conjunction with RIC systems to determine vegetation water demand was also examined. We conclude that the use of RIC systems for highway irrigation is feasible; support of multiple types of Communication Links (CLs) is a necessity; distributed intelligence, generic data acquisition support and alarm response features should be incorporated into the overall RIC system design; Caltrans maintenance hierarchy should be preserved when implementing RIC; a water manager position should be developed to aid in RIC implementation and operation; and a custom RIC system designed for highway right-of-way applications should be developed by Caltrans.

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EXECUTIVE SUMMARY

The ongoing drought has prompted business, government and the public to examine how California's water resources are used. After the current drought is over, the problems of an ever increasing population and overall growth in water demand will remain. While new water sources may be available in some areas, conservation of existing resources will be a major component in meeting tomorrow's needs. Caltrans is committed to decreasing the use of irrigation for highway right-of-way landscape, using reclaimed water where possible, and increasing the efficiency of existing irrigation systems.

The advent of sophisticated control and communication technologies has permitted the development of Remote Irrigation Control (RIC) systems. While originally designed for golf course irrigation, these systems are now being used in many highway applications. Water conservation, maintenance labor costs, personnel safety and other related issues support the need for Caltrans to explore the possibility of remotely controlling the programming and supervision of highway landscape irrigation.

This report presents an assessment of the "state-of-the-art" of RIC systems for highway right-of-way applications. The primary goal is to provide Caltrans maintenance personnel with a central reference source on the subject. The components of this study are: a survey of current RIC systems, an analysis of transmission methods used in RIC systems, a survey of current RIC expertise at Caltrans, and an examination of future trends and technologies.

A generic RIC model is used to enable system comparison. The components of this model are the Main Control Unit (MCU), the Communications Link (CL), and the Remote Site Controller (RSC). A set of benchmark features is also used to allow detailed comparison of the RIC systems surveyed in this report. The model and benchmark features are generic in nature and may be used to compare systems yet to be developed.

Functional descriptions and practical considerations for each CL transmission method are presented. The inherent advantages and disadvantages of each method have been explained to enable system designers to make application-specific decisions. The diversity of Caltrans district needs makes the support of hybrid CLs a necessity. The proper choice of a CL transmission method is critical to the successful implementation of remote irrigation control.

In order to aid irrigation optimization, RIC systems can implement "closed-loop" irrigation based on environmental feedback. The California Irrigation Management Information System (CIMIS) provides weather and evapotranspiration information to promote the use of evapotranspiration based irrigation. Weather stations can be used where CIMIS coverage is inadequate. Moisture sensors provide more localized feedback, but must be placed judiciously for proper operation. RIC systems offer varying degrees of support for these environmental feedback sources. The high cost of sensing equipment often makes extensive use of feedback impractical when multiple sensors are required. Generic data acquisition support is important to integrate future sources of environmental feedback. The ability to respond expediently to situations when irrigation should be suspended is also important.

Reclaimed water use for irrigation is expected to be more common in the future as it becomes more widely available. Caltrans' water conservation guidelines indicate a commitment to its use for highway applications. Often, this water source is subject to limitations on flow, volume or time of delivery. All irrigation projects must comply with any state and local regulations concerning the use of reclaimed water (time of irrigation, etc.). Also, exposing the public to treated effluents must be avoided. Many RIC systems readily support solutions to these constraints.

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Fourteen commercially available RIC systems are surveyed; those providing full central control for highway applications as of December 31, 1991, are also benchmarked. Some systems have been subsequently enhanced, discontinued or renamed.

Generally, most RIC systems surveyed are based on personal computers; operate in single-user mode; support time based irrigation programming and water budgeting; and feature distributed intelligence and varying degrees of data acquisition support. Hard wire, dial telephone and conventional radio are the most commonly supported CL transmission methods. Trunked radio use has been spearheaded by the Motorola MIR 5000 system and is now being supported by a few other systems.

The trends in RIC system design include more global system design approaches, more prevalent use of environmental feedback, emerging alternatives to time based irrigation programming, support for emerging communications technologies, increased levels of distributed intelligence, improved RSC user interfaces, and use of graphical user interfaces for the MCU software. The communications area will benefit from the expected growth in the wireless data communications market. Digital atmometers have the promise to become inexpensive alternatives to weather stations for ET driven irrigation.

One of the most successful ongoing Caltrans RIC projects is the Oceanside project in District 11. This MIR 5000 system has been used since 1988 for flow management and supervision of irrigation from a reclaimed water source. A Rain Bird Maxicom system is used by District 7 at the I-710 and State Route 60 interchange. This system uses flow monitoring and environmental feedback from a weather station. District 4 has implemented software to use Model 170 controllers as time-based RSCs. Remote operation and data acquisition support are forthcoming. Several new RIC projects are in progress in Districts 5, 6, 7 and 12.

The survey of Caltrans personnel yielded the following information. First, it is desirable to reflect the current maintenance hierarchy when deciding the area covered by individual RIC systems. System control should be at the maintenance supervisor level. A district (or regional) water manager position should be developed to provide assistance to maintenance supervisors in RIC system operation and water conservation methods.

Second, the most desirable RIC water conservation features are: quick response to hydraulic system failure; suspension of irrigation during unusual climactic conditions; affordable environmental feedback; and flow management. Expenditure limits for highway landscape irrigation set by the California Transportation Commission make it necessary to find the most cost effective solution on a case by case basis.

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TABLE OF CONTENTS

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LIST OF TABLES

Copyright 2011, AHMCT Research Center, UC Davis

LIST OF FIGURES

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CHAPTER 1

INTRODUCTION

The maintenance of highway irrigation systems is a very labor intensive task with exposure to traffic. As currently implemented, Caltrans maintenance personnel must inspect and adjust irrigation systems by physically driving to the system location, exiting the vehicle and making on-site automated controller changes. Time of irrigation, sequence of irrigation, etc. must all be modified this way.

One important way to reduce the field time necessary to supervise highway irrigation and increase irrigation efficiency is to implement a centralized control system. This would enable a small number of trained Caltrans personnel to take over the routine reprogramming and adjustment of highway irrigation systems. It would also allow the status supervision needed to respond to alarm situations, such as excessive flow, quickly. Additionally, a centralized control system would allow the application of water to be adjusted in response to environmental feedback. When weather conditions vary daily, such as in the spring and fall months, the vegetation's demand for water also varies. In order to maximize irrigation efficiency, water application should be matched to the demand. Without central control this may be theoretically possible but impractical due to limited resources and manpower.

Recent advances in computer and communications technologies have further extended the range of capabilities of remote irrigation control systems. The availability of small, inexpensive and extremely powerful microprocessors and memory chips have permitted the evolution of systems with distributed intelligence. This allows a landscape irrigation control system to have decision making capabilities resident in the field. New types of telecommunications, such as trunked radio, are now available to provide affordable coverage of remote areas. As a result, flexible and cost effective centralized control of systems distributed over large geographical areas is now possible.

In particular, drought conditions, increasing demands on water resources, maintenance labor costs, personnel safety and other related issues support the need for Caltrans to explore the possibility of remotely controlling the programming and supervision of highway landscape irrigation. As with any successful implementation of new technology, the potential benefits of such a system must be carefully weighed against the associated costs.

1.1 Problem Definition

As is common in a field experiencing rapid growth, current remote irrigation control systems are characterized by a wide diversity of features and implementations. Influences from applications in agricultural irrigation, golf course landscape irrigation, and municipal park system irrigation are prevalent in current system designs. This variety, while greatly enhancing the ability of the system designer to optimize performance, can make it difficult for Caltrans personnel to keep abreast of all possible system configurations.

Over the years, many Caltrans engineers, landscape architects and maintenance personnel have been involved with different aspects of remote irrigation control. This involvement has developed into a reservoir of considerable expertise. The problem for the rest of the organization is in accessing this knowledge base. The individuals involved are scattered

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throughout the state and a single source where this information is compiled is not readily available.

There is no comprehensive reference, within Caltrans or within industry, which contains the information necessary to give Caltrans personnel a working understanding of the equipment and methods used in remote irrigation control. Therefore, a reliable reference report is needed to aid department professionals in the investigation of such systems.

1.2 Objectives

There are four objectives that are clearly defined to satisfy the overall goal of providing a good reference source for Remote Irrigation Control (RIC) systems.

The first objective is to provide a thorough study of currently available RIC systems. This study is comprised of two components: system surveys and system benchmarks. The system surveys provide quick overviews of system configurations and features, while the benchmarks furnish more detail. The system surveys provide subjective assessments of system feature advantages and disadvantages, including aspects of water management and conservation. The system benchmarks do not provide such assessments but instead provide an objective and detailed list of system features. A brief field guide is also provided for quick reference use, in a separate booklet.

The second objective is to provide an analysis of the communication methods used by currently available RIC systems. This analysis is furnished in surveys that provide functional descriptions of the transmission methods and present practical considerations related to their use. The functional descriptions focus on RIC system operation. The practical considerations include discussions of reliability, topology, terrain considerations, licensing requirements, maintenance, and costs.

The third objective is to provide a survey of RIC expertise and information already existent within Caltrans. This component includes information derived from Caltrans' experiences with RIC systems and a discussion of typical RIC requirements for Caltrans applications.

The fourth objective is to provide an examination of future technological trends regarding centralized irrigation control. This component includes new irrigation programming features, new controller designs, new feedback instrumentation and applicable emerging technologies in the communications area.

1.3 System Terminology

Remote control systems enable an operator to exercise control upon a process or function at a distance. Often the locations of the remotely controlled equipment are at a substantial distance from the point of control. Telemetered data obtained from sensors at the remote site may be used to provide the feedback necessary for human or automatic decision making. The system may then formulate and communicate control signals to operate actuators effecting the desired action. Examples of remote control systems are ground-guided missiles,

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pipeline and utility control, space vehicle control, remote repair, submarine probes, etc. Remote control systems are also known as telecontrol systems.

In our application, the objective of the remote control system is to regulate water delivery at highway landscape sites for the maintenance of ornamental vegetation. The system may utilize feedback from environmental sensing equipment to apply water in the most efficient manner. Often, the application of fertilizers, pesticides and soil amendments is also required.

Current remote irrigation control (RIC) systems offer a variety of features and designs. The state of the industry is such that very few standards have been established. In order to compare the systems to be surveyed, it is necessary to model a generic telecontrol irrigation system. Our model has three main components (see figure 1.1): a Main Control Unit (MCU), a Communications Link (CL), and a Remote Site Controller (RSC). This model is explained after a brief presentation of the remote site irrigation equipment proper.

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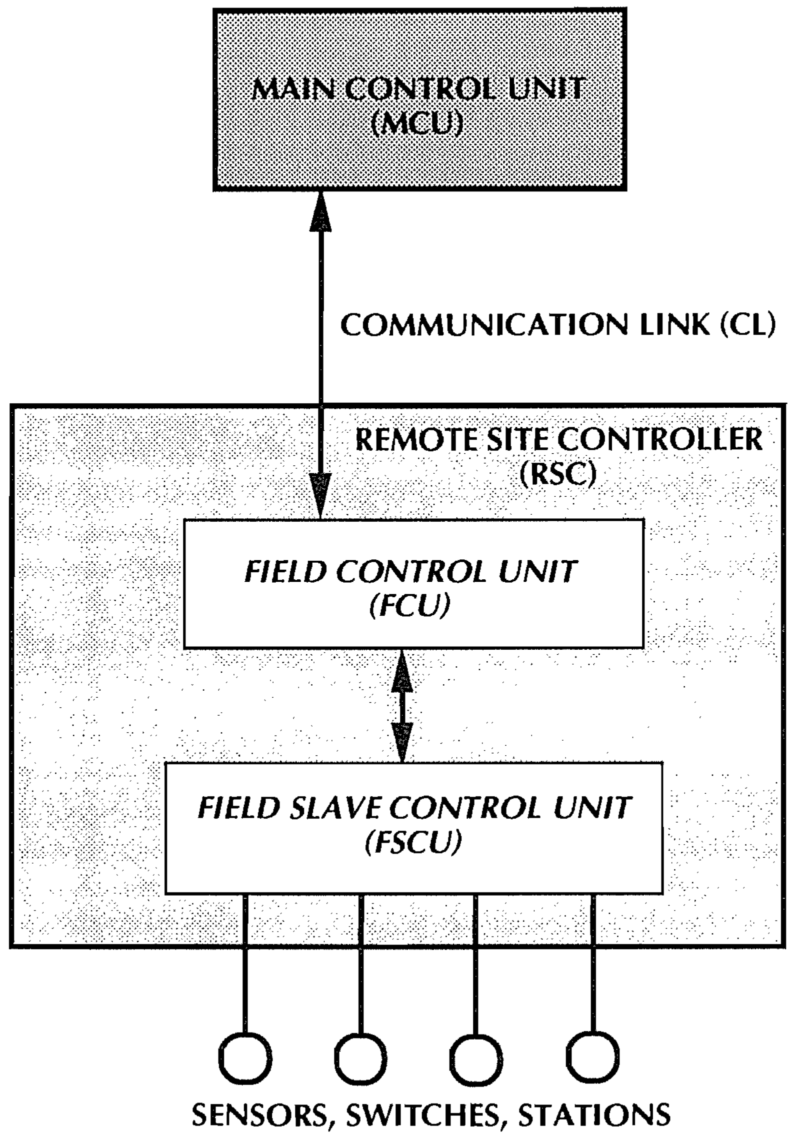

Figure 1.1 Remote Irrigation Control System Model

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1.3.1 Remote Site Irrigation Equipment

At the remote site, water from a source (such as a well or a local water company) is distributed to different points of application near the target vegetation by a hydraulic system. A typical hydraulic system might consist of pumping equipment, a main line pipe, several lateral line pipes, sprinklers, associated flow control valves, filters, and backflow prevention equipment.

A well designed hydraulic system provides adequate pressure and flow for uniform water delivery to vegetation with similar water requirements. In practical terms, it is not possible to deliver water with adequate pressure to all points of application simultaneously. Thus, the hydraulics impose a practical bound on the maximum instantaneous water volume that can be applied. This practical constraint must be considered in the process of scheduling irrigation. Actuation of water delivery commonly requires turning a pump on or opening a master valve, as well as opening a valve near the point of delivery.

Two methods of irrigation are common in landscape applications today. In sprinkler irrigation water is sprayed over a certain area of soil by a nozzle aimed at a particular angle from the vertical. The area of coverage provided by a sprinkler is typically a fraction of a circle whose radius is determined by the nozzle type and the applied pressure. Uniformity of application is affected by many factors including wind conditions, often making it desirable to suspend irrigation during high wind periods. A wide variety of sprinkler designs is available.

In drip or trickle irrigation small diameter pipes deliver water near the plant root system at a slow rate [28, p. 196]. The points of delivery along these pipes are called emitters, which sometimes consist simply of small perforations in the pipes. Water must be free of debris to avoid clogging the emitters. The area of coverage provided by a single emitter depends on the applied flow rate and soil type.

As mandated by the Caltrans' Water Conservation Policy, dated June 26, 1991, all future "...planting should be able to sustain itself on normal rainfall after establishment." The impact of this policy is that most RIC systems will be installed to retrofit existing irrigation designs to help conserve water. A detailed discussion of the hydraulic design of the water delivery system is beyond the scope of this report. This presentation focuses on the equipment involved in the remote actuation of water flow and the acquisition of data for feedback purposes.

1.3.2 Main Control Unit

The Main Control Unit (MCU) interfaces to the system operator by means of a computer. The MCU computer can be operated locally by typical terminal/keyboard interaction, remotely via modem, or, in one case, by means of a touch-tone telephone. The MCU computer is usually equipped with a printer to obtain hard copy reports. Some systems require separate communication interface units to be connected to the computer via a serial port. Other interfaces are implemented as add-in boards to be installed on the computer's motherboard. A few systems support the use of a mouse as an input device. Most systems surveyed operate in character mode, with only a few offering full graphics mode operation.

The MCU software allows access by the system operator to all the system features. System features can be divided between control specification features and supervisory features.

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As an example, a control specification might be to specify the amount of water to be delivered to a given location, while a supervisory feature might be to monitor the status of irrigation at that location.

Examples of typical facilities provided by MCU software are off-line irrigation programming (i.e., without being connected to a remote site during program creation), sending and receiving irrigation programs from the field, manual operation of Remote Site Controllers, weather data monitoring, flow monitoring, generation of reports, graphical display of data, etc. Additionally, the MCU software supports system configuration tasks such as address assignments, specifications of Communication Links, etc.

Some systems provide password protection to prevent unauthorized access to critical areas such as irrigation programs. In this way maintenance personnel may monitor system status and respond to alarms without accidentally modifying programming information.

1.3.3 Communication Link

The Communication Link (CL) enables transfer of information between the MCU and the Remote Site Controller. This function is effected by encoding the information in a signal that can be transmitted to the remote site through some transmission medium such as telephone cable or radio. The information is then decoded at the receiving end. Communication Links can be characterized by their transmission media, arrangement of connections from the MCU to the remote sites (topology), signalling scheme, error recovery techniques and information transfer rate.

Given the geographical distribution of Caltrans highway landscape sites, the choice of the CL becomes critical. RIC systems that are able to implement multiple CLs are desirable. This furnishes the designer with enough flexibility to provide full area coverage.

1.3.4 Remote Site Controller

The Remote Site Controller (RSC) effects control of water delivery and may acquire the local data to be used for feedback. Most RSCs surveyed can be operated locally at the remote site. A front panel user interface is provided for this purpose. Although microprocessor designs are prevalent, some RSCs provide electromechanical user interfaces consisting of dials and switches. A typical solid-state user interface consists of a Liquid-Crystal Display (LCD) and a keypad.

One of the major differences in RIC system design philosophies is the manner in which the decision-making process is distributed between the MCU and the RSC. The simplest systems concentrate the decision-making process at the MCU. While this simplifies RSC design and reduces its cost, it also increases the workload of both the MCU and the CL.

In more complex systems the RSC makes decisions on behalf of (and as specified by) the MCU. This design philosophy increases the overall reliability of the system because the RSC is able to continue operation in the event of a CL failure. Additionally, communication traffic with the MCU is reduced.

While some RSCs capable of autonomous decision-making consist of a single unit, others use a Field Control Unit (FCU) to control several Field Slave Control Units (FSCUs)

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(see figure 1.1) on behalf of the MCU. The FSCUs are responsible for generating the valve control signals and acquiring the feedback data. The field intelligence of these RSCs is concentrated at the FCU.

1.4 Benchmark Features

This section introduces the benchmark features used to compare the remote irrigation control (RIC)systems. The intent of this analysis is to provide Caltrans maintenance personnel with an in-depth presentation of system features for system selection.

The benchmark results do not provide a numerical score to compare each system. Such scoring is necessarily subjective and no single scoring scheme can take into account the diversity of site-specific application needs and irrigation philosophies present within Caltrans.

Instead, the benchmark features are meant to supplement the information contained in the system surveys, enabling each reader to find out individually which system best suits their application and irrigation philosophy. The benchmark results provide a list of features that may or may not be important to a particular system design, but that should be considered in the decision-making process. Only the reader can make the necessary judgement in adjusting the relative weights assigned to each benchmark feature.

The definitions are presented here in two main groups. The first group defines system features accessible from the Main Control Unit, the central point of operation of the system. The second group defines system features provided by the Remote Site Controller, the remote part of the system where the irrigation itself takes place. Within each group, features are further classified according to different functional categories. While most features are self-explanatory, some explanations are included to clarify further the meaning of certain features. These explanations are presented in a smaller font text following their corresponding feature.

The benchmark results are presented in tabular form in a later section. For each table, the features defined in this section correspond to the rows and the systems benchmarked constitute the columns. This arrangement provides a quick way to compare the different systems based on any of the functional feature categories. The benchmark feature definitions are presented next.

1.4.1 MCU Benchmark Feature Definitions

MCU Control and Display

- ❑ Maximum number of RSCs controlled
  - Largest existing system
- ❑ Maximum number of stations controlled
- ❑ Irrigation programmable by grouped station number

  This indicates the ability to assign an irrigation program to a station by specifying its user defined group and number, where the groups and numbers can be assigned arbitrarily.
- ❑ Irrigation programs storable and retrievable from MCU permanent storage

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- ❑ Irrigation programs transferable from RSC to MCU
- ❑ Irrigation programs transferable from MCU to RSC
- ❑ Irrigation programs transferable from one RSC to another via the MCU
- ❑ Confirmation prompt used for accepting major setting or irrigation program changes
- ❑ Programmable download time for irrigation programs

  This indicates the ability to schedule the time at which an irrigation program is to be automatically downloaded to a RSC.
- ❑ Programmable irrigation program execution suspension

  This indicates the ability of the MCU to specify a period of time during which irrigation is suspended for purposes of maintenance, pre-planned events, etc.
  - Immediate irrigation program execution suspension
- ❑ Assignment of a "default" irrigation program for RSC on system start/reset

  This indicates the ability to assign an irrigation program to all of the RSCs in the system at the time the system is started or reset.
- ❑ Notification of alarm from RSC when RSC irrigation program is changed on site

  This indicates the ability of the MCU to notify the user whenever a RSC irrigation program is altered by maintenance personnel at the RSC location.
- ❑ Assignment of program/routine to be executed in response to a specified alarm

  This indicates the ability of the MCU to respond to a specified alarm in the system with a set of user defined actions.
  - User defined actions are downloadable to RSC
- ❑ Separate screen display for "alarm warnings"

  This indicates the ability of the MCU to produce a display of the alarms in the system.
  - Grouped by RSC
  - Grouped by stations
  - Grouped by area
  - Time stamped
  - Hard copy report
- ❑ Separate screen display for summary

  This indicates the ability of the MCU to produce a display of the system status.
  - Summary display of RSC status and conditions
- ❑ Separate screen display of intended vs. actual irrigation history

  This indicates the ability of the MCU to show the difference (perhaps produced by device failures, water budgeting, etc.) between the irrigation program specified by the user and the irrigation program executed by the system.
  - Grouped by RSC
  - Grouped by stations
  - Grouped by area
  - History length
  - Hard copy report
- ❑ Simultaneous access of all RSCs for system start up/shutdown
- ❑ MCU password protection
- ❑ Assignment of new RSC local password via MCU
  - System wide
  - By RSC

<u>MCU Irrigation Program</u>

- ❑ Access to all RSC irrigation scheduling features

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This indicates the ability of the MCU to provide remotely all the RSC irrigation scheduling features available locally at the RSC as opposed to being restricted to a subset of those features.

❑ Station "on time" adjustment by percent multiplier

This indicates the ability of the user to specify the duration of irrigation as a percent of a reference setting. This feature is often referred to as "water budgeting" and is used to increase irrigation efficiency in periods of unusual climatic conditions.

- Adjustment by station group
- Adjustment by RSC group
- System wide adjustment
- Preservation of original irrigation program at RSC

❑ Irrigation program adjustment based on evapotranspiration rate

This indicates the ability of the MCU to adjust a given irrigation program based on evapotranspiration measurements.

- Grouped by area
- Manual entry
- Automatic entry
  - •• Value averaging

    This indicates the ability of the MCU to adjust the irrigation program to account for sudden climatic changes.
- Evapotranspiration rate adjustment factor

  This indicates the ability of the MCU to adjust the irrigation program based on a percentage of reference evapotranspiration rate data to account for different vegetation, slope, exposure, etc.
- Soil model based adjustment factor

  This indicates the ability of the MCU to adjust the irrigation program to account for rainfall, evapotranspiration rate, soil capacity, and soil infiltration rate.

❑ Theoretical "on time" flow projection

❑ Fine adjustment of start time

❑ Fine adjustment of water shutdown delays

The above two features indicate the ability of the MCU to finely adjust the indicated irrigation start and end times. This ability reduces the strain on the site water supply system (pump or water supply piping) due to transients produced by valve openings and closures. Remote control of this feature is an aid to field personnel adjusting system sections where one water supply system feeds several RSC sites.

<u>MCU Data Acquisition</u>

❑ Maximum number of analog data acquisition inputs

- Threshold alarm

  This indicates the ability of the MCU to produce an alarm when a measured quantity exceeds a specified value. For example, a rainfall input indicating a value of 1/2 inch with a threshold of 1/4 inch will trigger an alarm.
- Data value monitoring

  This indicates the ability of the MCU to display the value of a specified quantity, e.g, the temperature at a certain location.
- Data labeling

  This indicates the ability of the MCU to allow the user to refer to measured quantities symbolically. For example, "Temperature at Hwy 99 and I-5."
- Data scaling

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This indicates the ability of the MCU to allow the user to scale incoming data values to be represented in different unit systems. For example, multiplying an incoming solar radiation value in W/m^2 by 0.001 to yield KW/m^2.

- Data manipulation

  This indicates the ability of the user to define new variables as functions of sensor data values acquired by the system. For example, the weekly average of a sensor data value.

  - •• Arithmetic combination of multiple inputs
- Threshold point setting

  This indicates the ability of the user to define the value of a data input at which an action is triggered.
- Data display

  This indicates the ability of the MCU to display selected data acquisition values in a variety of modes.

  - •• Display of user defined analog sensor readings
  - •• Text mode
  - •• Graphics mode
- Permanent data storage

  This indicates the ability of the MCU to store data values in permanent memory.

  - •• Manual
  - •• Automatic
    - ••• Variable upload frequency
- Hard copy report

❑ Maximum number of pulse (rate) data acquisition inputs

This indicates the maximum number of pulse (rate) variables sampled by the system, e.g., flow rates.

- Pulse (rate) alarm

  This indicates the ability of the MCU to produce an alarm when a measured pulse (rate) quantity exceeds a specified value. For example, a flow rate input indicating a value of 20 Gpm with a threshold of 10 Gpm will trigger an alarm.
- Pulse (rate) monitoring
- Data labeling
- Data scaling
- Data manipulation
  - •• Arithmetic combination of multiple inputs
- Threshold point setting
- Data display
  - •• Display of user defined pulse (rate) sensor readings
  - •• Text mode
  - •• Graphics mode
- Permanent data storage
  - •• Manual
  - •• Automatic
    - ••• Variable upload frequency
- Hard copy report

❑ Maximum number of digital data acquisition inputs

This indicates the maximum number of boolean (bistate) variables sampled by the system.

- State alarm

  This indicates the ability of the user to define the state of a data input at which an alarm is triggered. For example, trigger an alarm if a switch becomes open.
- State monitoring
- Data labeling

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- Data manipulation
  - •• Boolean combination of multiple inputs

    This indicates the ability of the user to define new variables as functions of boolean data acquired by the system.
- Data display
  - •• Display of user defined digital sensor readings
  - •• Text mode
  - •• Graphics mode
- Permanent data storage
  - •• Manual
  - •• Automatic
    - ••• Variable upload frequency
- Hard copy report

❑ Maximum number of system wide status queries per day per RSC to MCU

This indicates the maximum number of times status information can be collected from a RSC in a single twenty four hour period by the MCU.

- Variable status query frequency
- Average time for status query per RSC

<u>MCU to RSC Communication Link Hardware</u>

❑ Two way communication with RSC

❑ Simultaneous support of multiple transmission media

This indicates the ability of the MCU to use heterogeneous transmission media to communicate with the RSCs in the system.

❑ Hard wire interface

Assume message transfer reliability to be equal on all hard wire systems.

- Minimum number of signal wires required
- Shielded cable required
- Simple interconnect engineering

  This means, for example, that wire sizing is not required, etc..
- Reduction of hard wire distance to the MCU for each RSC

  System topology determines hard wire distance. In a bus topology a single run of cable is used to connect the MCU to all of the RSCs; in a ring topology there is a single run of cable but it loops back to the MCU; in a star topology there is one run of cable per RSC connected to the MCU. Generally, a bus topology has the smallest hard wire distance requirement, followed by ring and star topologies.
- Maximum signal cable length

❑ Radio interface

- Return channel capability
- RF carrier sensing capability

❑ Trunked radio interface

❑ Cellular telephone interface

❑ Dial telephone interface

❑ Private line telephone interface

- 2-wire circuit
- 4-wire circuit

<u>MCU to RSC Communication Link Software</u>

❑ Information transfer error checking

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This indicates the ability of the MCU to exchange information with the RSC sites while maintaining the highest possible data integrity.

- Single direction, multiple transmission with parity or checksum
- Dual direction transmission with acknowledge and checksum
- More sophisticated error checking

❑ Communications equipment failure feedback

This indicates the ability of the MCU to detect and report failures in communications equipment.

- Data integrity alarm
- Transmission failure alarm
- Failure log in summary display

❑ Communication can be initiated by MCU or RSC

❑ Interface to different models of RSC of the same vendor

<u>MCU Computer Requirements</u>

❑ Minimum computer requirement

❑ "Off-the-shelf" computer configuration

This indicates minimal user assembly or setup is required.

❑ Operating system requirement

❑ Minimum RAM requirement

❑ Hard drive requirement

❑ Color Monitor/Card required

<u>MCU Utility, Peripheral and Related Functions</u>

❑ Terminology used throughout software user interface

❑ Operation of the MCU via modem with a second computer

❑ Alarm condition paging

❑ MCU need not be present after download

❑ Background tasking of system program

❑ Weather station interface

- Maximum number of weather stations system will support
- Seamless interface
- Complete evapotranspiration rate data
- Hard wire interface
- Radio interface
- Trunked radio interface
- Cellular telephone interface
- Dial telephone interface
- Private line telephone interface

❑ California Irrigation Management Information System (CIMIS) interface

- Seamless interface

❑ Menu driven operation

❑ Context sensitive help

❑ Program and data storage on floppy disk

❑ Multiple display mode support

❑ MCU program in color

❑ Graphics printer support

❑ Screen saver

❑ Optional mouse support

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- ❑ Foreign language support

<u>MCU Supports</u>

- ❑ Easy to learn software
- ❑ Free technical support
- ❑ Free on-site system analysis
- ❑ Free software updates
- ❑ Upgrade continuity between hardware and software

1.4.2 RSC Benchmark Feature Definitions

<u>RSC Control and Display</u>

- ❑ Maximum number of independently accessible stations
    - Maximum rms current output per station at 24 VAC
    - ~~Maximum total rms current output at 24 VAC~~
- ❑ Station circuit short indicator
    - Shorted station(s) disabled automatically
    - Shorted station(s) logged automatically
    - Alarms MCU indicating station short
- ❑ Station circuit open indicator
    - Open station(s) disabled automatically
    - Open station(s) logged automatically
    - Alarms MCU indicating station open
- ❑ Pump start / master valve circuit
- ❑ Programmable irrigation program execution suspension

  This indicates the ability to specify a period of time during which irrigation is suspended for purposes of maintenance, pre-planned events, etc.
    - By day of the week
    - By date
    - By time of day
    - Locally programmable
    - Downloadable from MCU
        - Locally stored and executed
- ❑ Manual operation via hand held radio
    - Through MCU
    - Radio unit on RSC
- ❑ Manual operation without disrupting irrigation program

  This indicates the ability to execute commands entered by a local operator and then resume execution of the existing irrigation program.
- ❑ Assignment of the same irrigation program to all stations
- ❑ Assignment of an existing station irrigation program to other station(s)
- ❑ Irrigation program(s) downloadable from the MCU
- ❑ Irrigation program(s) uploadable to the MCU
- ❑ Maximum number of different irrigation programs storable in non-volatile memory
- ❑ Maximum number of days of actual irrigation history storable in non-volatile memory
- ❑ Menu driven format for command and display
- ❑ Access to irrigation program and other critical functions is password protected
- ❑ Assignment of new RSC local password via MCU

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- ❑ Confirmation prompt used for accepting major setting or irrigation program changes
- ❑ Alarm MCU when the irrigation program has been locally altered

RSC Stand Alone Capability

- ❑ Autonomous execution of RSC timing, irrigation program and control features
    - Maximum duration of autonomous operation

RSC Irrigation Program

- ❑ Access to all scheduling features accessible from MCU
- ❑ Maximum duration of station "on time"
    - Resolution of station "on time"
    - Number of station "on times" per twenty four hour period
    - Variable "on time" durations within any twenty four hour period
    - Set "on time" by start time and duration
    - Set "on time" by start and stop times
    - Set "on time" by volume
    - Set "on time" by precipitation
- ❑ Maximum number of days in the irrigation cycle
    - Variable cycle period
- ❑ Station "on time" adjustment by percent multiplier

    This indicates the ability of the user to specify the duration of irrigation as a percent of a reference setting. This feature is often referred to as "water budgeting" and is used to increase irrigation efficiency in periods of unusual climatic conditions.
    - Preservation of original RSC irrigation program
    - Range of adjustment
    - Resolution of adjustment
- ❑ Infiltration rate/slope compensation

    This indicates the ability of the user to adjust the irrigation program so that any single station "on time" will not cause runoffs.
    - By station
- ❑ Flow driven scheduling

    This indicates the ability of the user to define a target flow for a particular station group. The sequence of the irrigation program is then automatically adjusted to match the total flow.
- ❑ Fine adjustment of water shutdown delay
- ❑ Fine adjustment of station start time

RSC Data Acquisition

- ❑ Maximum number of analog data acquisition inputs
    - Additional circuitry required for analog data acquisition
    - Data value monitoring

        This indicates the ability of the RSC to display the value of a specified quantity, e.g, the temperature at a certain sensor.
    - Data labeling

        This indicates the ability of the RSC to allow the user to refer to measured quantities symbolically. For example, "Temperature at Hwy 99 and I-5."
    - Data scaling

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This indicates the ability of the RSC to allow the user to scale incoming data values to be represented in different unit systems. For example, multiplying an incoming solar radiation value in W/m^2 by 0.001 to yield KW/m^2.

- Threshold point setting

  This indicates the ability of the user to define the value of a data input at which an alarm or action is triggered.

- ❑ Maximum number of pulse (rate) data acquisition inputs

  This indicates the maximum number of pulse (rate) variables sampled by the system, e.g., flow rates.
  - Additional circuitry required for pulse (rate) data acquisition
  - Pulse (rate) monitoring
  - Pulse (rate) alarm

    This indicates the ability of the RSC to produce an alarm or action when a measured pulse (rate) quantity exceeds a specified value. For example, a flow rate input indicating a value of 20 Gpm with a threshold of 10 Gpm will trigger an alarm.
  - Data labeling
  - Data scaling
  - Threshold point setting
- ❑ Maximum number of digital data acquisition inputs
  - Additional circuitry required for digital data acquisition
  - State monitoring
  - State alarm

    This indicates the ability of the user to define the state of a data input at which an alarm or action is triggered. For example, trigger an alarm if a switch becomes open.
  - Data labeling
- ❑ Non-volatile data storage
  - Maximum number of data points

<u>RSC to MCU Communication Link Hardware</u>

Since no system allows control of RSCs from different vendors, all communication interfaces supported by the MCU of a given vendor are supported by their respective RSCs.

- ❑ RSC telecontrollable without the addition of circuitry
- ❑ Signal line surge protection

<u>FCU to FSCU Communication Link Hardware</u>

- ❑ FCU and FSCU are an integrated unit

  This is the case for single component RSCs, i.e., those contained in a single box.
- ❑ Hard wire interface available

  Assume message transfer reliability to be equal on all hard wire systems.
  - Minimum number of signal wires required
  - Shielded cable required
  - Simple interconnect engineering
  - Reduction of hard wire distance to the FCU for each FSCU

    System topology determines hard wire distance. Generally, a bus topology has the smallest hard wire distance requirement, followed by ring and star topologies.
  - Maximum signal cable length

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- Regeneration of control/status signals at each FSCU

- ❑ Radio interface available

FCU to FSCU Communication Link Software

- ❑ Command and verify sequence on all FCU to FSCU communications

RSC Power

- ❑ Phantom (signal line) power capability
- ❑ Solar power capability
- ❑ 110 to 125 VAC power capability
    - Power line surge protection

RSC Miscellaneous Considerations

- ❑ RSC clock accuracy
- ❑ Battery backup for RSC clock/timing functions
    - Battery backup duration
- ❑ Automatic daylight savings time clock correction
- ❑ Enclosure lightning protection
- ❑ Stainless steel housing for all RSC electrical and electronics
- ❑ Easily accessible (from housing exterior) electrical connections
    - Barrier strip connections for stations
    - Barrier strip connections for signal
- ❑ Foreign language option for command and display

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CHAPTER 2

COMMUNICATION LINK TRANSMISSION METHODS

2.1 Communication Problem Definition

The goal of a communications system is to transfer information reliably between two systems. For purposes of remote irrigation control this concerns transmitting irrigation commands from a Main Control Unit (MCU) to a group of Remote Site Controllers (RSCs) and also transmitting feedback data from the RSCs back to the MCU.

The function of the Communication Link is to bridge the distance between the operator and the system under control. Communications should be fast enough so that (as perceived by the operator) commands are executed immediately and alarm conditions are reported expediently. They must be reliable, not only in the sense of being free of errors, but also with respect to access to the link; busy signals are not acceptable. And they must be transparent, that is, the operator should be able to exercise control without being aware of which type of link is used or how the information is being transferred.

Consider a familiar example of a communications system, the way people communicate by speech. The original message (an idea) is translated by the speaker into pressure variations that are transmitted through the air to the listener's ear, and are then translated back into an idea.

First, notice that the form of the message used for transmission is different from its initial and final forms. In other words, the message is encoded, transmitted over a channel associated with a physical medium, and then decoded.

Second, message transmission is susceptible to "noise" (a signal not containing information pertinent to the message being transmitted) and attenuation over distance (it is harder to hear someone far away).

Third, the receiver must be able to separate the noise from the message. Some communication schemes add information to the message to enable the receiver to detect transmission errors (the person hearing the speech listens to the message within the context of the conversation).

Finally, the receiver might require a retransmission if the message received doesn't make sense (perhaps due to noise corruption). Or it might send an acknowledgement that the message was received successfully (yes, I understand what you said).

In general, more complicated systems (networks) are required as both the number of users and the source to destination distance increases. Two of the most widely known communication networks are the mail and telephone systems. In these systems the destination must be specified, that is, the message must include an address. Also, the message must be routed, which means that one out of the (possibly) many paths in the system must be chosen (not necessarily by the sender).

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Communication networks are very complex and can be classified in a variety of ways regarding their different attributes. For example, networks can be classified by type of message (e.g., voice, data, video), transmission media, speed, capacity, arrangement of connections (topology), etc.

The following is a presentation of key concepts involved in the understanding of data communication systems.

2.2 Frequency and Bandwidth

Signal frequency content and channel bandwidth are important concepts regarding electronic communication systems.

First, any electronic signal of finite energy can be expressed in terms of sinusoidal component signals of different frequencies [16, p. 38]. These electronic signals are band limited, which means that their frequency components have significant values only within a finite range of frequencies. For example, voice signals have components with frequencies between 20 Hertz to 20,000 Hertz.

Second, communication media can only transmit signals having components within a particular range of frequencies (the bandwidth). Frequency components outside this range are not transmitted, resulting in loss of information. Therefore, this property determines which signals can be transmitted with integrity by a given medium. For example [18, p. 37], telephone equipment is designed to transmit frequencies between 300 Hertz and 3000 Hertz. This set of frequencies corresponds to the pitch and intonation where human speech produces its maximum intelligibility. The bandwidth of the telephone equipment is matched to the bandwidth of the signal that is normally transmitted over it (human speech).

2.3 Analog and Digital Communications

Analog communications use transmission signals that can have a continuous range of values like those produced by speaking into a microphone. There is a correspondence (analogy) between the air pressure levels and the electrical energy produced by the microphone. Transmitting this signal over a pair of wires to an audio amplifier is an example of unmodulated analog communications [13, p. 145]. In other cases the information to be transmitted is modulated onto a sinusoidal carrier signal. Three types of modulation are possible depending on which property of the carrier is made to correspond to the information being transmitted [15, p. 196]: amplitude, frequency, or phase. The inverse process performed at the receiving end is called demodulation.

In contrast, digital communications use signals that can only take discrete values (usually two) like those used in telegraph communications [12, p.5]. One of the values can correspond to a signal condition such as current flow or voltage, while the other value can correspond to the opposite condition such as no current flow or no voltage [13, p. 52]. Digital communications require greater bandwidths than their analog counterparts for the same information transfer [63, p. 5]. The advantage to digital communications is that they are less susceptible to noise and allow implementation of sophisticated error correction techniques.

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Originally used to transmit computer data, there is a current trend toward increased use of digital communication for other types of information. For example, voice communications over most telephone networks today involve conversion of the original analog signals to digital form, digital transmission, and then reconversion to analog form.

2.4 Multiplexing

Multiplexing refers to a set of techniques that allow transmission of multiple messages over the same communication line. The inverse process is called is called demultiplexing. There are two strategies for multiplexing messages, time-division multiplexing (TDM) and frequency-division multiplexing (FDM) [15, p. 238].

In TDM users are periodically allocated full use of the transmission facility for a specified time. Statistical time-division multiplexing is a special case of time-division multiplexing where time slots are assigned only to those users having a message to transmit [16, p. 157]. TDM is most naturally suited for digital communications. As an example, assume three computers need to transmit data over a common line using TDM. The multiplexer provides three time slots of equal duration. During the first time slot, data from the first computer are transmitted over the line; during the second time slot, data from the second computer are transmitted and so on. At the other end the demultiplexer routes data received during the first time slot to the first computer and so on. Data from different sources are not transmitted simultaneously but rather in strict sequence.

In FDM the total bandwidth of the line is subdivided and each transmission is allocated a frequency band. FDM is most naturally suited for analog communications. This is the concept behind radio and television systems. As an example, assume the same three computers now use FDM for transmission. Three carriers of different frequencies are provided, one for each data source; the carrier frequencies are spaced enough to avoid interference. Each data signal modulates it respective carrier and the resulting modulated signals are sent over the transmission facility. At the other end, filters are used to "tune in" to the modulated carriers. Each signal is then demodulated and routed to its respective destination. In this case, data from different sources are transmitted simultaneously over different frequency bands.

2.5 Simplex, Half Duplex and Duplex Systems

Communication systems can be classified according to the direction of transmission. Most textbooks define this classification as follows [16, p. 143] [63, p. 242].

In a simplex system transmission is possible in one direction only, while half-duplex (HDX) and full-duplex (FDX) systems support two-way communications. In a half-duplex system transmission is possible in both directions but only one-way communication is possible at a time. In a full-duplex system simultaneous transmissions in both directions are possible. This is the definition used in this report.

In contrast, both the Institute of Electrical and Electronic Engineers (IEEE) and the ITU Radio Regulations define a simplex system to be one where transmission can occur in both directions but not simultaneously [23].

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According to the CCITT R.140 definition, a half-duplex system is capable of simultaneous transmission in either direction, but can only transmit in one direction at a time by virtue of the terminal equipment involved [23]. The definition of full-duplex is the same as given before.

It should be noted that there is a substantial amount of confusion and inconsistency in the use of these terms in communications literature. In particular, RIC system manufacturers often use these terms without giving any indication of which convention they follow in their documentation.

2.6 Data Formatting

A data message consists of a set of values, characters or codes. Data values are usually represented in a binary numbering system where the smallest form of information is the bit (a one or zero value). In parallel communications all the bits corresponding to a data value are transmitted simultaneously over parallel channels. In contrast, serial communications involve transmitting bits one at a time over a single channel. Long-distance data communications are generally serial in nature.

Data are formatted for purposes such as synchronization, error detection, and to increase channel utilization. For example, in some types of serial communications it is usual to provide start, stop and parity bits to each transmitted character [12, p. 99]. The start and stop bits are used to indicate the beginning and end of the character, that is, to synchronize the transmission. The parity bit provides means of detecting transmission errors by indicating whether the number of ones in the character is odd or even.

At a higher level, the entire message might be formatted with additional characters for the same purposes, i.e., to indicate the beginning and the end of the message, to indicate the destination of the message, etc. [16, p. 263] Moreover, some communication networks require that messages be transmitted in fixed length units called packets [16, p. 267].

2.7 Error Detection and Error Correction

The general idea behind error detection is to include (as part of the message) the result of applying a predefined mathematical function to the message data. Checksum and Cyclic Redundancy Checks are common error detection methods used with block data transfers [21, p. 368] [15, p. 265]. The same mathematical function is applied to the received data and the result compared to the one sent by the transmitter. If the values of the result differ, a transmission error must have occurred. Alternatively, errors can be detected by echoing the received data to the original transmitter where it is checked against the original.

Error correction schemes fall in two categories: retransmission schemes and forward error correction (FEC) schemes [15, p. 263] [21, p. 367]. The former retransmit the message when an error is detected, either as a response to a request by the receiver, or automatically when echo checks are used. The latter involve encoding the data with special codes that enable the receiver to detect and correct errors without retransmission. Examples of forward error

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correction codes are the Hamming and BCH codes [15, p. 271]. Retransmission schemes will, in general, decrease the throughput of the system in noisy environments.

2.8 Asynchronous and Synchronous Communications

Data transmission requires timing to decide when each symbol or character is being received. Timing schemes can be classified as either synchronous or asynchronous.

Asynchronous transmissions use a specific start and stop convention to indicate the beginning of each character [15, p. 137]. This type of transmission originates in applications where characters are presented to the communication system at a slow and unpredictable rate such as when a user types information at a computer terminal. In this example such characters are transmitted asynchronously between the keyboard and the computer. The most common asynchronous scheme uses a start bit and a stop bit to frame each character (an additional parity bit is used for error detection). The start and stop bits provide the synchronization required between the independent clocks at each end [16, p. 145]. Each bit in the character is assumed to have the same duration, but the timing between characters is random. Thus, the recognition of each bit in the character depends on the ability of each clock to maintain the same timing independently.

Synchronous transmissions establish a common clock between stations to transmit blocks of characters such as the ones needed to transmit commands from a Main Control Unit to a Remote Site Controller as a response to a user selection. The required timing information may be included in the data waveform or as a separate signal [16, p. 146]. Synchronous schemes avoid the overhead of framing each character in the block by framing the entire message with a start sequence and an end sequence [15, p. 139]. In this case the clocks at each end cannot be independent because slight drifts in their timing would result in transmission errors during the process of recognizing each (unframed) character in the block [16, p 145]. As an example, IBM's Binary Synchronous Communications (BISYNC) protocol uses character sequences (as opposed to bit sequences) to frame each message [16, p. 256]. Two SYN characters mark the beginning of the message, while two ETX or ETB characters mark the end of the message text and are followed by two check code characters.

2.9 Topology

Topology refers to the way communicating entities are connected. The basic topologies are star, bus, and ring [13, p. 574]. A star topology provides a separate link from a central component (called a "hub") to each of the other components in the system. In a bus topology components are connected "in line," all sharing the same link. A bus with trees is identical to a standard bus, except that at any point along the link additional paths may be added which branch from the "in line" configuration. A ring topology is similar to a bus, but the link "loops back" to the first component.

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2.10 Communication Link Surveys

The following section presents surveys of the Communication Link technologies used by currently available RIC systems. The purpose of this section is to provide information regarding the advantages and limitations offered by each transmission method.

The surveys have two parts. The first part provides a functional description of the transmission method. This presentation is focused on RIC data communication applications. The second part discusses practical considerations that must be taken into account when selecting a transmission method for a RIC system. These practical considerations include reliability, topology, terrain considerations, maintenance requirements, licensing requirements and costs.

2.10.1 Hard Wire

Functional Description

Hard wire systems transmit signals over metallic media consisting of two or more wires. The MCU to RSC hard wire interconnect cabling is provided, installed and maintained by the end user. Most of the RIC systems surveyed support communications over a single cable pair. Multiple pair systems do exist, but are not as common due to increased cabling costs.

Signals transmitted over wires suffer both amplitude and phase distortions that are functions of frequency. In other words, the strength of the different frequency components is reduced and they travel at different velocities (therefore arriving at different times). As a result, not only is there a limit on the range of frequencies that can be transmitted, but there is also a limit on the total distance of the wire. In the case of data transmission, this distortion also means that there is a limit on how fast the data can be transmitted.

Digital signals have such a wide bandwidth that they cannot be transmitted directly over wire except for very short distances [15, p.192]. Data streams with rates below 19.2 Kbps can be transmitted digitally up to 2000 feet by using line drivers. Most drivers transform the digital signal provided to them into a more noise immune electrical (but still digital) format. At the distant end, the format is then converted back into the original signal type.

In order to be transmitted by wire cable over longer distances, the digital signal must be modulated onto an analog carrier [12, p. 75]. The modulation process has the effect of reducing the total bandwidth required for transmission as well as shifting the band of transmit frequencies. This process is key to extending data transmission distances. The fundamental idea is to match the analog signal band and bandwidth to that which the hard wire cable transmits best. At the distant end, the analog signal is demodulated, which translates it back into a digital format. The device used to modulate and demodulate the digital signal is called a "modem".

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Short-haul modems can transmit data for distances of up to ten miles and they usually cost less than standard telephone modems [15, p.192]. These modems are designed to operate only on hard wire cable pairs so their analog bandwidth requirements are less stringent. They can also be used on special local loop telephone circuits. These circuits have no loading coils or other bandwidth altering devices in place. Most short-haul modems in use today require a full four wire connection to function. One pair (two wires) is used to transmit and one pair is used to receive. Most of the weather stations used on RIC systems for environmental feedback will support a short-haul modem connection.

Standard two-wire telephone modems operated in a "non-dial" mode are used for most hard wire RIC communications. The modems may be built into the RSC and may operate at different speeds, but they are still essentially telephone modems. Voice telephone lines have a bandwidth extending from 300 Hertz to 3000 Hertz. As a result, the modem must translate the data into a signal which can be transmitted within this band. This usually entails utilizing fairly complex equalization and filtering circuitry. The advantage to using this type of system is that the connection of RSCs to the hard wire becomes a simple matter of bridging onto the cable pair. Also, the hard-wire communications signal is media independent and can be connected to several other types of transmission equipment (such as radio) with very little conversion. Another advantage is the lack of a DC signal component; this usually means that the selection of wire size as a function of distance is much less critical.

Hard wire systems exhibit "loading" when devices (such as RSCs) are connected to them, i.e., energy drained by the connections contributes to overall signal degradation. As a result, there is a limit on the number of devices connected to a given system.

The range of a hard wire link can be extended by means of a repeater. The simplest kind of repeater amplifies the line signal (and the noise it contains as well). In contrast, regenerative repeaters receive the data, reconstruct it, and then retransmit it. The regenerative repeater is preferred since the signal reconstruction removes all noise and other signal impairments.

Twisted pair cable consists of two insulated copper conductors twisted together. The twisting cancels coupling (crosstalk) into and from adjacent conductors and increases signal integrity. Susceptibility to noise can be further minimized by shielding the cable. Some systems require a flat paired cable such as #14-2 rather than a twisted pair. All manufacturers fully specify the type of cable(s) required by their system.

While the specific method of operation for each RIC system is different, the overall operation is similar. The MCU is connected to the hard wire through a proprietary interface unit. All of the RSCs on the system are each assigned a unique address. When the MCU needs to communicate with a particular unit, that unit's address is included in the data being exchanged on the hard wire. The addressed unit recognizes that it is the RSC being called and responds. Command and status information exchange then takes place. By having the MCU initiate and control the information transfer, the situation of having more than one RSC attempting to communicate is avoided.

Reliability

The reliability of a hard wire system is good when properly designed. The location of the cable route should be far removed from any site power cabling. Power cables have the potential of inducing various types of noise into the hard wire signal. This is especially true if the power cable is feeding a large inductive load, such as a pump motor. Care should be taken

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to insure that all connections are in a location that will remain dry. Excessive moisture can lead to conductor corrosion, which may compromise the integrity of the signal connection. Additionally, underground splicing should be avoided. While there are products available to aid in providing a moisture barrier at underground connections, insuring this is difficult and corrosion often results. Exposure to lightning can cause some damage even when surge protection and additional protective circuitry are provided. Most hard wire failures will be related to breaks and/or shorts in the cabling. Careless excavation during the installation of sign posts, guard rails, paddle markers, etc. are the most likely sources of cable breaks. Although significantly increasing RIC installation costs, PVC conduit should be considered for cable routes near the pavement.

Topology

While hard wire systems can support all types of topologies, a bus and its tree derivatives are the most common in RIC systems. Bus and tree topologies work well for typical highway landscape applications which are linear in nature. The primary disadvantage is that equipment failure or a break in the cabling can render part of the system inoperative (the RSCs beyond the break). Ring topologies become costly for great distances due to the return path to the MCU. However, they offer the possibility of quickly recovering from a break in the cable by transmitting over the return link.

Terrain Considerations

Installation of a hard wire CL into existing sites will usually be impractical. The cable should be buried for both aesthetic reasons and to preserve its integrity. In a retrofit application, existing piping and plant locations may be in the way. For new projects, proper cabling can be installed while the site is under construction. All cable routes should be planned to accommodate future highway expansion.

The installation of a CL which is entirely hard wire is often difficult due to easement problems from the MCU to the highway right-of-way. However, a hybrid arrangement of both hard wire and telephone local area data channels (discussed in a later section) may be practical for certain new projects.

Maintenance Requirements

Most repairs due to accidental cable breaks can be performed without the need for expensive test equipment. Usually, a volt-ohm meter is sufficient to test for continuity and benchmark resistance values. On rare occasions, a problem may occur when there is no evidence of excavation or other suspicious activities. In this situation, it may be necessary to hire a contractor with the appropriate test equipment (such as a Time Domain Reflectometer) to find the problem.

Any hard wire installation should always be designed for ease of testing. This entails implementing a topology and connector system that is easy to sectionalize in case of trouble. Also, it is important that correct wiring records be maintained.

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Licensing Requirements

There are no special licensing requirements for hard wire systems.

Costs

The costs associated with installing a hard wire CL are very site and RIC system specific. Each manufacturer provides complete hard wire cable specifications for their system. Often the RIC system dealer can provide the necessary cabling at a greatly reduced price for large system quantities.

Table 2.1: Typical Hard Wire Costs

ITEM	COST
Direct bury cable, type as specified by RIC manufacturer	Cost is site and system specific; typical costs per 1000' range from $170 for direct burial flat cable, to $570 for direct burial shielded twisted pair cable
Trenching and installation	Cost is site specific, estimate on a case by case basis
Easement agreements	Cost is site specific, estimate on a case by case basis

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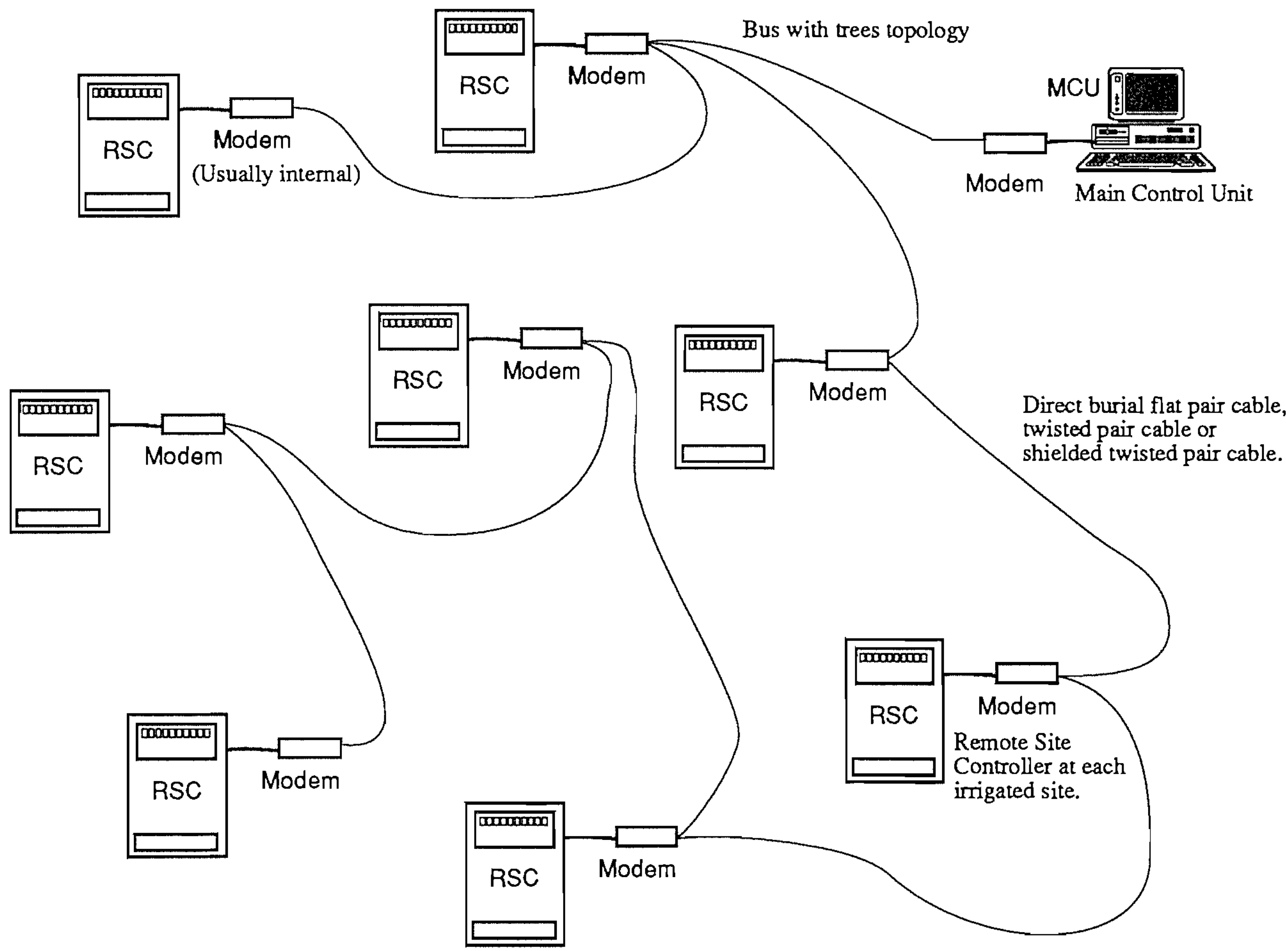

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Figure 2.1 Hard Wire Communication

2.10.2 Dial Telephone

Functional Description

In this section we survey the use of dial telephone service for data communications over analog voice circuits. This service is provided by the Public Switched Telephone Network (PSTN), which requires dialing to establish a connection (as opposed to private line service, which employs dedicated circuits). This is probably the most ubiquitous means of communications in existence today. Private line and cellular telephone services will be discussed separately.

The major elements of the modern telephone system are the station apparatus, transmission facilities, switching facilities, and signaling.

The station apparatus consists of the telephone set or, in the case of a RIC system, a modem which is connected to the MCU computer or RSC. As explained for hard wire systems, modems are necessary in order to transmit data over analog telephone voice channels [12, p. 75]. Asynchronous data rates ranging from 300 bps to 2400 bps are currently supported over switched telephone lines with standard modems. Higher data rates usually demand better line quality and the use of more expensive modems featuring proprietary, non-standardized modulation techniques [13, p. 428].

Transmission facilities are comprised of the different media and equipment used to carry information between geographical locations; for example fiber optic cable. Both Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM) are used to dramatically increase the number of channels on a given physical medium [1, p. 213] [1, p.403]. Facilities include twisted pair cable, coaxial cable, fiber optic cable, terrestrial microwave radio and satellite radio. The capacities achieved by these systems range from 24 to 180,000 two-way voice circuits, with fiber optic systems boasting the highest capacity [6, p. 73].

Switching facilities establish the circuit connections between stations and various transmission facilities.

Signaling refers to the control aspect of making a call; for example dial tones, busy signals, recorded announcements, etc.

The subscriber's modem is connected to a Central Office (CO) by a twisted pair circuit called the local loop. The CO is the part of the network closest to the subscriber's premises and is where the first stage of switching is performed.

There are three types of switching offices. Local COs present the first level of switching. Tandem offices provide switching between local offices and Toll offices provide switching into the long-distance network [6, p 83].

The connection between the different types of switching offices is accomplished by trunk circuits. Message trunks, as they are commonly called, provide a voice/data path that is used as a segment of the circuit necessary to complete a call [1, p. 173]. Multiple trunks may link several different switching offices together in order to complete a call. The trunk concept allows a relatively small number of dedicated circuits to be reused for different calls at different

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times. This takes advantage of the fact that at any one time the actual number of calls in progress will be small when compared to the total number of subscribers connected to the network.

It should be noted that during times of unusual events, such as earthquakes, large fires, etc., the call traffic upon the network can become extremely heavy. During these times the above assumption often breaks down and more calls are attempted than there are trunks available. The excess trunk requests are then blocked by the switching equipment resulting in an incomplete call. Often the disparity between requests and available facilities is so great that a total communication network failure results.

On January 1, 1984 the entire long distance and local telephone system in the United States was divided. Several regional and long distance telephone companies are now required to compete for subscribers. As part of the Modification of Final Judgement (the legal ruling which implemented the breakup) 160 Local Access and Transport Areas (LATAs) were formed across the country [6, p.185]. LATAs are areas or regions which define the nature of telephone traffic within or across their borders. Calls originating within and terminating within the same LATA are considered non-toll calls and must be provided by a local telephone company, also called a Local Exchange Carrier (LEC). Those calls crossing LATA boundaries are considered toll or long distance calls and must be provided by a long distance telephone company, also known as an Inter Exchange Carrier (IXC).

When a subscriber initiates a call, the RIC system computer or controller provides "off hook" and "dial" commands through the serial data port connection to the modem [6, p.140]. The modem then places a DC short on the local loop. The switching equipment in the CO recognizes this condition as an "off hook" and provides the local loop with a "dial tone" audio signal. After a brief delay the modem begins sending Dual Tone Multifrequency (DTMF or Touch Tone) digits that correspond to the distant end telephone number. The switching equipment at the CO recognizes the number and provides this information to the message switching network, which in turn determines an appropriate call route.

Calls to subscribers serviced by a different CO within the same LATA are switched onto intra-LATA trunks. Long distance calls are switched onto the toll network over inter-LATA trunks [6, p. 3].

At the distant end Central Office the switching equipment acquires the local loop which is assigned to the called telephone number. If the loop is not in use the equipment sends an interrupted 20 Hertz, 105 volts AC "ringing generator" signal to the distant end subscriber. The distant end modem "answers" the call after a predetermined number of ring cycles by placing a DC short on the local loop, thereby going "off hook." The distant end modem then transmits an "answer" carrier tone of 2400 Hertz (for a Bell 212A or V.22bis type modem) to the originating end. The originating end responds by sending an "originate" carrier tone of 1200 Hertz and the connection is complete. The two sites can then exchange data.

Reliability

California is served by several different local telephone companies. Often the reliability of the local telephone network is assumed to be uniform across the state. Unfortunately, this is not a good assumption. Many areas have fairly poor service, which may be manifested by a high number of incomplete calls or noisy transmission. Often the poor service is due to aging cable facilities, antiquated CO equipment or both. While much of the problem occurs in rural areas, this is not always the case. Many urban areas also have poor service.

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For most RIC applications only local calls will be used to communicate between the MCU and the RSCs. It is very important that the local telephone service at each of the RSC sites be tested before deciding to use dial telephone for a Communication Link. This can be accomplished by simply traveling to each area and placing several calls back to the MCU site. While complicated technical measurements can be performed to evaluate transmission quality, they are usually not necessary. If all calls are completed, the completion is executed quickly and the connection is fairly noise free, it should be adequate for a RIC system. As an added safeguard, a portable lap top computer with a modem should be used to establish several data communication test links with the MCU. The links should be established using the same data transmission rate as the RIC system.

One should also be aware that in emergency situations, the public telephone network's capacity is often exceeded. While service is usually restored quickly after the emergency has subsided, this is not always the case. If facilities are permanently damaged by the event, long outage periods may result.

Topology

Most RIC systems which support dial telephone must have a single line connected to each RSC. Some systems are able to have several RSCs hard wired together and then link them to the MCU via a single dial telephone line. These requirements limit the system to a star or modified star topology.

None of the systems surveyed are capable of handling simultaneous telephone calls. As a result, a dial telephone Communication Link is not capable of supporting communication to more than one site at a time. It should be noted that the delay involved in establishing and releasing connections sequentially for calling a large number of sites is appreciable. Also, simultaneous transmission of commands to all sites would be impossible.

Terrain Considerations

Accessibility to telephone service is related to population density. In urban areas, the points of connection to the PSTN are most often located very close to the RSCs. Easement agreements for the routing of drop cables may be necessary at some sites. Further analysis must be done on a site by site basis.

Maintenance Requirements

The local telephone company is responsible for maintaining all equipment up to the network interface at the subscriber's premises. Therefore, maintenance is limited to local wiring, modems, etc.

Field testing is limited to the simple tests described in the reliability section. Purchase of a test telephone set for maintenance personnel should be considered.

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Licensing Requirements

There are no special licensing requirements for dial telephone service.

Costs

The pricing shown below is typical of that found in the major metropolitan areas of the state. The actual price of service for a specific site may vary slightly. Each Caltrans district has a telephone coordinator who oversees all orders for service. Some districts have negotiated lower rates with the local exchange carrier(s). The appropriate coordinator must be consulted to obtain exact price quotations for a specific district.

The RSC sites will require the installation of a pole for an overhead drop cable or the trenching and covering of an underground drop cable. The telephone network interface should be placed in a locked weather-proof enclosure to prevent unauthorized access. Usually the interface can be mounted inside the pedestal which contains the RSC.

Table 2.2: Typical Dial Telephone Costs

ITEM	COST
Basic activation fee (per line for installation at MCU and each RSC)	$70.75
Pole installation for overhead drop (per site)	Incurred only if overhead drop is used, cost is site specific, estimate on a case by case basis
Trenching and covering for underground drop installation (per site)	Incurred only if underground drop is used, cost is site specific, estimate on a case by case basis
Easement agreements	Cost is site specific, estimate on a case by case basis
Basic monthly rate (per line, at business rate)	$8.35
Federal access charge (per line, per month)	$4.14
Per outgoing call charge (day rate, toll charges extra)	$0.04 for first minute, $0.01 for each additional minute

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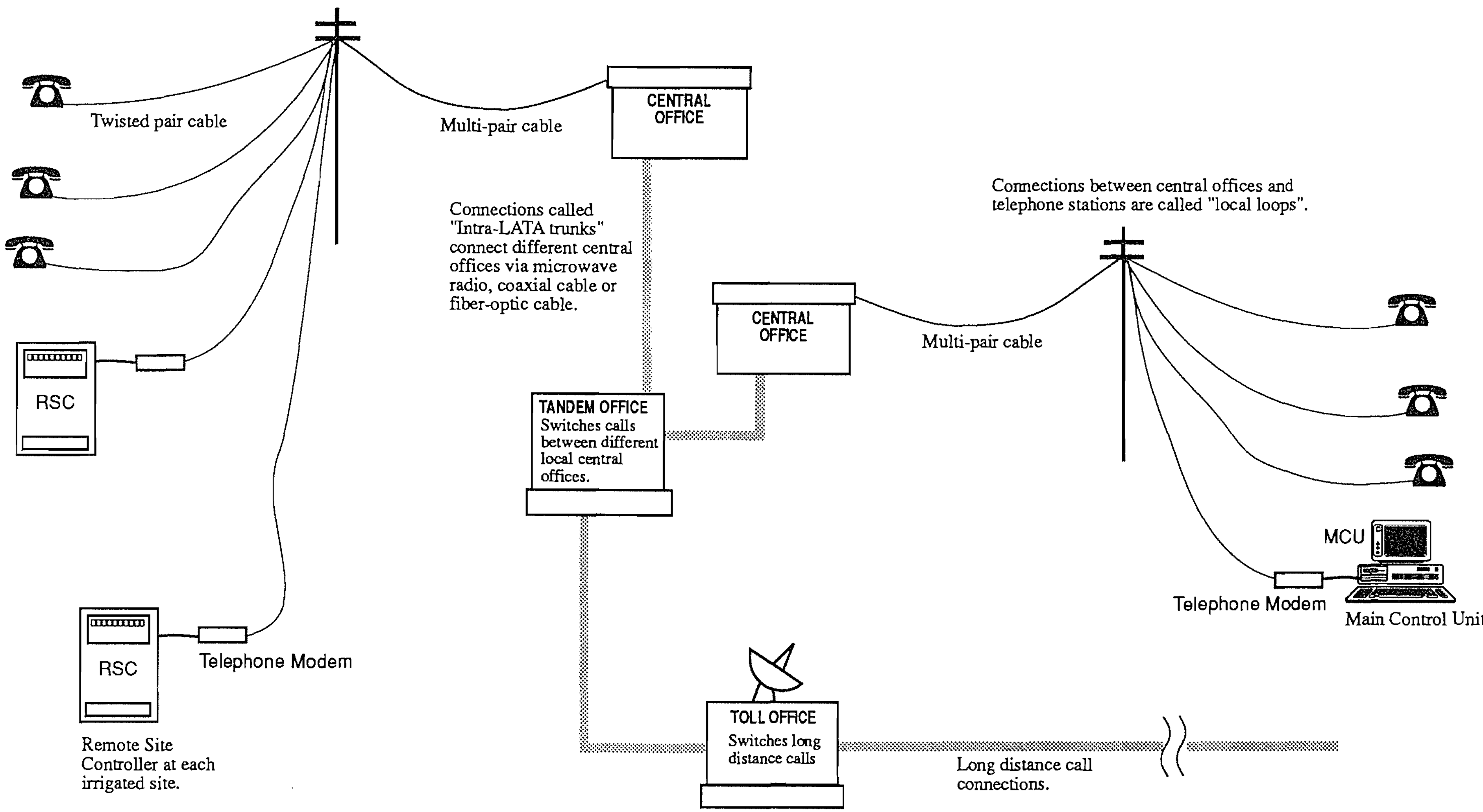

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Figure 2.2 Dial Telephone Communication

2.10.3 Private Line Telephone

Functional Description

In this section we survey the use of private line telephone service for data communications over analog voice circuits. This service overcomes some of the limitations of dial telephone by providing dedicated lines leased to the subscriber.

There are several types of private line services available but only two of them relate to data communications for RIC purposes: data transmission channels (3002 type) and local area data channels [14, p. 322].

Data transmission channels offer point-to-point and multipoint service, with support for both half-duplex and duplex operations. Special conditioning is available to improve the transmission characteristics of these channels in support of higher data rates. Modems are still required as in dial telephone systems. Peak data rates of 19.2 Kbps are possible on good quality leased lines [13, p. 428].

Local area data channels are used for limited distance data transmission, for example, intrabuilding or cross-campus applications with ranges of up to six miles. Data transfer rates up to 19.2 Kbps are supported by these channels with use of inexpensive short-haul modems. This type of service is very similar to a hard wire system, the primary difference being who owns and maintains the cable facilities.

A point-to-point layout uses a data transmission channel to establish communications between two fixed stations. In the RIC application the two points would be the MCU and an RSC or group of RSCs. The channel is connected to the nearest CO at each end. The circuit is completed between COs by connecting to various interoffice facility channels. The circuit layout is very similar to a dial telephone connection with the major difference being that the voice/data path is not switched, but permanently wired. An additional difference is that there is no signaling or "dial tone" (for "off hook," "on hook," etc.); the information contained within the data that is transmitted and received determines circuit usage and activity.

Multipoint data transmission channel layouts implement a star topology and require a bridge to interconnect several different circuit "legs." The bridge distributes the analog modem signal between the different legs in the transmit direction [14, p. 331]. In the receive direction it combines the signal from each leg. The bridge has no way of interpreting the analog signals being passed through it. The associated equipment at the bridging point also provide amplification, equalization, and test access.

As applied to RIC, a multipoint circuit would be used to communicate with the entire system. The MCU would be connected to the master leg and each RSC would be connected to a leg emanating from the bridging point. More complicated designs might incorporate more that one bridging point. There are no currently implemented RIC systems that use this type of Communication Link. However, some systems can support this kind of arrangement. This type of CL is used in non-RIC applications within Caltrans. As an example, the Traffic Operations Center in Los Angeles uses a multipoint private line network to communicate with about 750 Model 170 controllers.

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Even though both two-wire and four-wire facilities are available, the latter are preferred for most multipoint designs [14, p. 330]. Four-wire facilities dedicate a separate pair of wires for transmission in each direction, supporting both half-duplex and duplex operation. In contrast, two-wire facilities transmit and receive over the same pair of wires. For duplex two-wire operation, the circuit data rate must be reduced because the transmission band (300 to 3000 Hertz) is divided. Part of the band is used for transmit and part for receive. It should be noted that most duplex data transmission circuits are actually four wire after the first CO and the main distinction is how the circuit is built on the local loop. Of the RIC systems surveyed which would operate with a private line CL, all supported two-wire operation only.

Local area data channel and data transmission channel services do not offer regenerative repeaters. As a result, noise and other impairments added to transmissions are cumulative throughout the system. A multipoint topology allows the MCU to issue simultaneous commands to all stations without the delays involved in dialing. Finally, the subscriber is able to add equipment to monitor and manage the network.

The general operation of a RIC system using either type of CL is very similar to what was described for hard wire. The MCU is connected to the master leg of the circuit through an interface unit. All of the RSCs on the system are each assigned a unique address. The MCU has control of the system and decides with which field unit it needs to communicate. That unit's address is included in the data being transmitted on the master leg. The packet or block of data which contains the address and request information is usually called a "poll." The RSC with the correct address responds to the poll with an "answer back." The answer back contains an acknowledge code and the requested status information. After information transfer is complete the MCU continues its polling sequence and addresses the next RSC. This type of architecture has drawbacks, e.g., the RSCs cannot interrupt the MCU when they need to communicate. But, a properly designed system overcomes these by having enough intelligence at the field unit that critical decisions can be made on site. Also, the polling cycle should be kept as short as possible.

It is possible to have an asynchronous communications architecture where RSC interrogation takes place infrequently and the RSCs are allowed to attempt communications when they have information to be transferred. All systems of this type involve some mechanism for resolving collisions (two RSCs trying to transmit at the same time). The exact method varies from system to system but usually works as follows. The RSC sends a burst of data to the MCU; if the MCU sends an acknowledgement back, the RSC knows communication took place. If no acknowledgement is received, the RSC assumes a collision and, after a random time interval, tries again. This continues until communications is established or a predetermined number of attempts have occurred.

Reliability

The reliability of private line telephone service is adequate for RIC applications in most areas. As with dial telephone, the quality of service is not uniform across the state. Some areas with aging cable facilities or outdated CO equipment may have poor service.

In some urban areas a private line circuit may cross telephone company boundaries. This may result in added repair delay during service outages.

On larger multipoint networks, some legs may become a chronic source of transmission errors. This can result in a high amount of down time for the associated RSC sites.

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Topology

Private line telephone supports both point-to-point and multipoint connections. Most RIC systems surveyed use two-wire, two-point circuits where a different line is provided to each site. This kind of arrangement implements a star topology with the hub located at the MCU. The Motorola MIR 5000 system does support a two-wire multipoint data transmission channel Communication Link. Because the circuits are dedicated, all stations can listen to the master (the MCU) and are able to be addressed simultaneously.

Terrain Considerations

As with dial telephone, accessibility to private line telephone service is related to population density. In urban areas, the points of connection to the network are most often located very close to the RSCs. In some areas private line service may not be available. Before committing to this type of CL, the local telephone service provider should be consulted regarding service to all RSC locations. Easement agreements for the routing of drop cables may be necessary at some sites. Further analysis must be done on a site by site basis.

Maintenance Requirements

The local telephone company is responsible for maintaining all equipment up to the point of demarcation at the subscriber's premises (RSC site). Therefore, maintenance is limited to local wiring, modems, etc.

Licensing Requirements

There are no special licensing requirements for private line telephone service.

Costs

The pricing shown below is the Caltrans rate for service provided by Pacific Bell. As with dial telephone, the district telephone coordinator oversees all orders for private line service. It should be noted that monthly charges are based on distance, not on circuit usage.

The RSC sites will require the installation of a pole for an overhead drop cable or the trenching and covering of an underground drop cable. The line termination equipment must be placed in a locked weather-proof enclosure to prevent unauthorized access. Four-wire terminating equipment requires more physical space than a standard network interface and it requires 120 VAC power. If space permits, the interface can be mounted inside the pedestal that contains the RSC.

Type of service: Data transmission channel (3002 type). The price is the same for four-wire half duplex, four-wire duplex and two-wire duplex circuits.

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Table 2.3: Typical Private Line Telephone Costs, Data Transmission Channel Service

ITEM	COST
Installation fee for two sites from the same CO (include MCU)	$716.00
Installation fee for additional sites from the same CO (per site)	$357.00
Pole installation for overhead drop (per site)	Incurred only if overhead drop is used, cost is site specific, estimate on a case by case basis
Trenching and covering for underground drop installation (per site)	Incurred only if underground drop is used, cost is site specific, estimate on a case by case basis
Easement agreements	Cost is site specific, estimate on a case by case basis
Monthly charge for two sites from the same CO (include MCU)	$55.88
Monthly charge for additional sites from the same CO (per site)	$27.94
Monthly mileage charge between COs	
01 to 10 miles	$5.23 per mile
11 to 15 miles	$3.16 per mile
16 to 20 miles	$3.01 per mile
21 to 60 miles	$2.64 per mile

Type of service: Local area data channel. This service is limited to a point-to point circuit from one Central Office.

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Table 2.4: Typical Private Line Telephone Costs, Local Area Data Channel Service

ITEM	COST
Installation fee	$716.00
Pole installation for overhead drop (per site)	Incurred only if overhead drop is used, cost is site specific, estimate on a case by case basis
Trenching and covering for underground drop installation (per site)	Incurred only if underground drop is used, cost is site specific, estimate on a case by case basis
Easement agreements	Cost is site specific, estimate on a case by case basis
Monthly charge	
Four-wire circuit	$55.88
Two-wire circuit	$37.58

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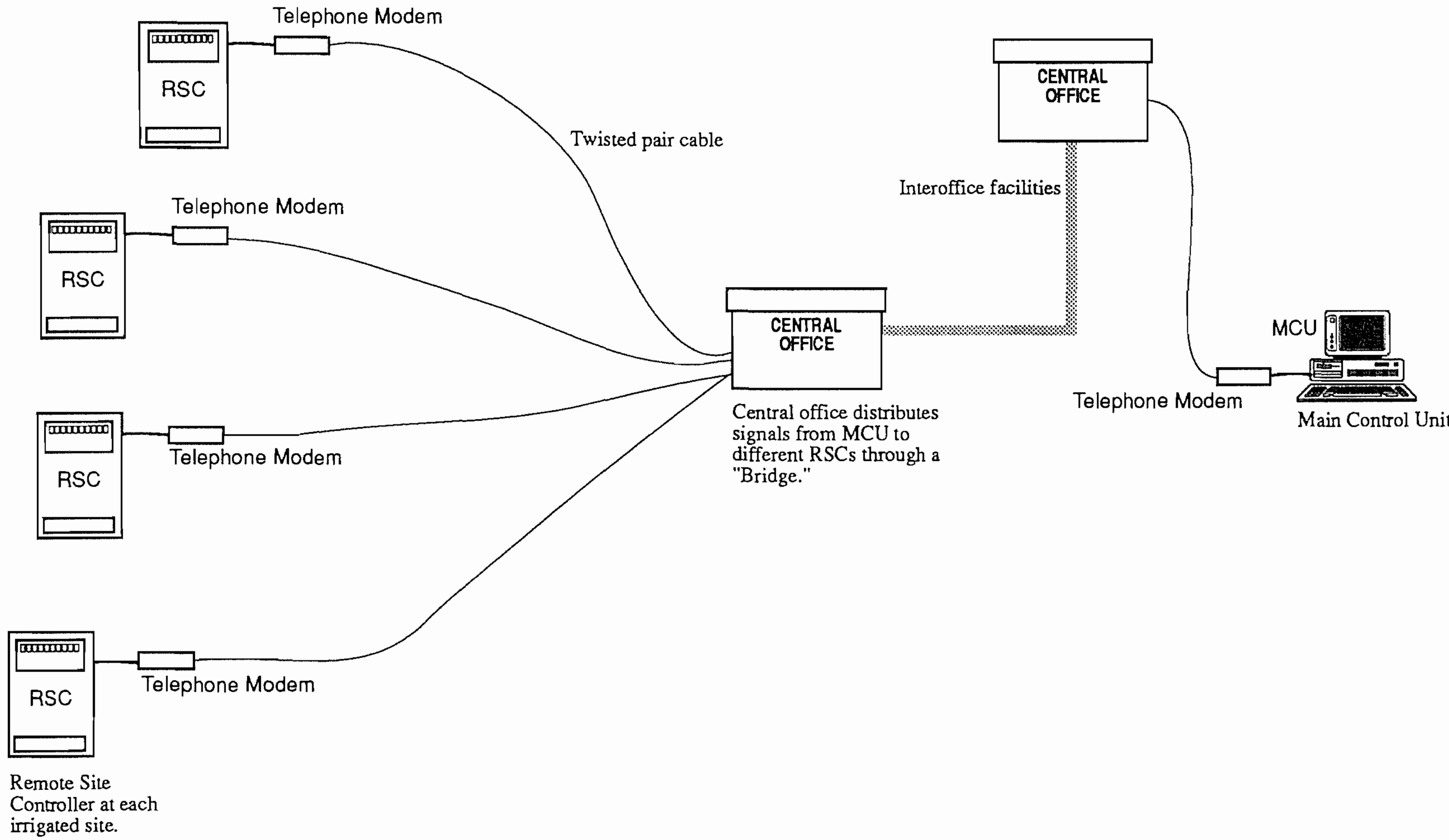

Figure 2.3 Private Line Telephone Communication

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2.10.4 Cellular Telephone

Functional Description

In this section we survey the use of the Advanced Mobile Phone Service (AMPS) for data communications over analog voice circuits. The name "cellular telephone" refers to the fact that the service area is divided into small geographical cells. Although usually depicted in hexagonal shape, actual cells have varying shapes and sizes. In most systems these cells are further grouped as clusters of seven cells each. There are three components in the AMPS system: cell sites, a mobile telephone switching office (MTSO), and the mobile units [1, p. 600]. The MTSO supervises and controls the operation of the system.

The mobile units communicate via 800 MHz radio with the cell sites, which are linked to the MTSO via land lines. The MTSO in turn provides switching and access onto the Public Switched Telephone Network (PSTN). The connection between the MTSO and a cell site is comprised of two data links used for control purposes, and a voice trunk for each of the voice channels assigned to the cell. The cell site houses the base radio station. Several transmitters are connected to a common antenna through combiners. The receivers use a separate antenna. Typical antennas are 100 to 300 feet high.

The spectrum allocated for cellular radio is split so that service can be provided by both a non-wireline carrier and a wireline carrier (a telephone company), in effect supporting two different systems called A and B, respectively [11, p. 154]. A band of frequencies is allocated for communications from the cell sites to the mobile units; channels in this band are called forward channels. Similarly, a different band of frequencies is allocated for communications in the opposite direction, with channels in this band known as reverse channels. There are 416 two-way channels available to each carrier system. Of these, 21 are assigned as set-up channels to carry signaling information to establish calls. The rest are used as narrowband FM voice channels. With clusters of 7 cells each, approximately 60 different voice channels may be assigned per cell. Each cell is also assigned its own set-up channel. By repeating the cluster pattern, a large area can be serviced while minimizing co-channel interference.

The station apparatus at the mobile unit used for voice communications consists of a control unit, a transceiver/logic unit, and a small mobile antenna [1,601]. In the case of RIC data communications, the station apparatus also incorporates a cellular modem or telephone line simulator interface. Cellular modems offer CCITT V.21 and V.23 compatibility and support data rates of up to 1200 bps [13, p. 629]. The line simulator interface allows the mobile unit to connect any dial telephone modem to the system through a RJ-11 (standard telephone) connector. The control unit is composed of a handset, a pushbutton keypad and alerting indicators [1, p. 601]. The transceiver provides duplex operation on any of the possible voice channels. Low power transmission levels of about 6 watts are used to minimize co-channel interference. Each mobile unit has an identification number based on the subscriber's 10-digit telephone number and a code identifying the home system.

When power is applied to the mobile unit, it tunes to the strongest set-up channel signal received and then monitors the 10 Kbps data stream [1, p. 605] [6, p. 152]. To initiate a call the mobile unit requests service over the set-up channel by sending its identification number and the desired telephone number. The base station at the cell site relays this information to the MTSO over land lines. The MTSO then assigns a voice channel to the mobile unit and forwards this information to the mobile unit via the cell site. When the mobile unit has

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acquired the assigned voice channel, the MTSO establishes a conventional PSTN circuit to the called party.

When the MTSO receives a connection request for a mobile unit, it instructs the cell sites to page the unit over their forward set-up channels. The mobile unit again tunes to the strongest set-up channel signal when it recognizes it is being paged. It then responds by sending its identification number over the newly acquired set-up channel. A voice channel assignment is subsequently transmitted by the MTSO. Once the mobile unit has acquired the assigned voice channel, the MTSO directs the cell site to send a data message to the mobile unit over the voice channel in order to start ringing.

While the call is in progress, the base station sends supervisory tones over the voice channel to be echoed back by the mobile unit. When the echoing ends the base station assumes the mobile unit has stopped transmitting. A signaling tone is sent over the voice channel by the mobile unit to request the call to be disconnected.

During the course of a call, the signal strength of the reverse channel is monitored by the MTSO in a process called locating. When a drop in this signal level is detected, the MTSO seeks another cell to service the call. Once a suitable cell is found, the mobile unit is requested by the MTSO to tune to the new assigned channels while the MTSO switches trunks. The process of changing cells is known as "hand off" or "hand over." The MTSO sends hand off commands over the voice channel by blanking out the voice signal for a 50 ms during which a burst of data is transmitted. The hand off process takes about 200 ms to complete. Although not important for voice communications, the loss of circuit during this process must be taken into account for data communications. For RIC applications the RSCs are at fixed locations, therefore, no movement between cells takes place and hand off blanking is minimized.

Calling from a mobile unit located in a foreign cellular area is possible only if billing agreements exist between the two systems. Making a call to such a mobile unit is more complicated because its location must be known to either the home system or the subscriber making the call. Some systems are designed to recognize foreign mobile units and automatically request their home system to forward their calls.

As subscriber density increases in any given area the call load on the corresponding cells also increases. In order to alleviate the cell congestion it is often necessary to further subdivide existing cells. This process involves reducing the range of currently operating sites and adding new cells to make up the coverage. As the size of the cells decreases, the frequency of hand off for traveling mobile units increases.

For RIC applications cellular telephone is used in exactly the same way as standard dial telephone. In fact, the MCU has no way of differentiating between a site which uses a cellular telephone number and one using a traditional wired dial telephone line.

The MCU initiates a call by providing "off hook" and "dial" commands through the serial data port connection to the modem. The modem then places a DC short on the local loop. The switching equipment in the CO recognizes this condition as an "off hook" and provides the local loop with "dial tone." After a brief delay the modem begins sending Dual Tone Multifrequency (DTMF) digits which correspond to the cellular telephone number. The switching equipment at the CO recognizes the number and provides this information to the message switching network, which in turn determines a call route to the appropriate MTSO. After the connection is made with the cellular mobile unit (by the sequence described earlier) the line simulator interface unit provides a "ringing generator" signal to the modem through the RJ-11 connector. The cellular end modem "answers" the call after a predetermined number of ring cycles by placing a DC short on the connector cable (as if it were on a regular telephone

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line). This "off hook" condition is recognized by the line simulator interface unit and the audio connection is completed. The cellular end modem then transmits an "answer" carrier tone to the MCU modem. The MCU modem responds by sending an "originate" carrier tone of a different frequency and the connection is complete. The two sites can then exchange data.

Reliability

In the past five years the number of cellular telephone subscribers has undergone a dramatic increase. This fast paced growth has prompted a rapid expansion in the area covered by cellular service. Good quality coverage is currently available in all major metropolitan areas, most medium sized towns, many small sized towns and along most major highways.

For RIC applications the problems associated with truly mobile operation are eliminated since the RSCs are stationary. This means that from a radio path standpoint, if the cellular link is initially acceptable it will remain so. As with any radio based service, quality of service tests should be conducted at every planned RSC location before a final decision to implement this type of CL is made. Portable cellular telephones with data modems are readily available for initial site testing. Data from a lap top computer at the test site should be transferred to the MCU over the cellular system. This transmission test should be performed at the same data rate that the RIC system uses.

As the number of subscribers increases, the load upon the cellular system can become extreme. This excessive loading can cause the system to fail to keep up with service demand. When the instantaneous number of cell users exceeds the available number of channels, a "busy" condition is encountered as the MCU or RSC attempts to place a call. The result can be the temporary inaccessibility of a RSC site. This problem can become quite pronounced along major commuting arteries at peak travel times. Most service providers try to take corrective measures by splitting cells as was discussed previously. Eventually, the minimum cell size is reached and, until a higher capacity cellular system is developed, RSC inaccessibility could be a problem in some areas.

For RIC applications it should not be a serious difficulty since most irrigation program modifications are downloaded at night when cell loading is light. However, the problem could hamper the timely reception of system status and alarm information.

Topology

As with dial telephone, most RIC systems must have a single cellular telephone connected to each RSC. Some systems are able to have several RSCs hard wired together and then link them to the MCU via a common cellular telephone connection. These restrictions limit the system topology to a star or modified star.

None of the systems surveyed are capable of handling simultaneous telephone calls. As a result, a cellular telephone Communication Link is not capable of supporting simultaneous system-wide transmission of commands. The delay involved in establishing and releasing RSC connections sequentially on a large system is appreciable.

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Terrain Considerations

Cellular telephone is a UHF radio based wireless telephone system. As such, an unobstructed line of sight path from each RSC location to the nearest cell site is necessary. Implementation of a RIC system may involve the combination of standard dial telephone and cellular telephone Communication Links, the latter being used when the cost of connecting a site to the PSTN by cable is prohibitive.

Maintenance Requirements

The end user has the responsibility of maintaining all customer owned cellular telephone equipment [75]. In most applications, the equipment is sold as part of the RIC system. Therefore, Caltrans is required to provide for the repair of any malfunctioning cellular telephone unit.

Caltrans has an existing contractual agreement with Cellular One for cellular telephone service. They also offer a service contract for equipment repair after the warranty period expires. Maintenance contracts may be purchased through normal contracting channels on a district by district basis.

Licensing Requirements

The cellular mobile unit FCC license is held by the service provider [76]. Therefore, as an end user, there are no direct licensing requirements.

Costs

The price of cellular telephone service and associated equipment varies throughout the state. The primary factors affecting price are the complexity and features of the cellular telephone equipment and the geographic location of service. For RIC applications, systems which offer this type of CL usually have specific cellular telephone equipment that is recommended by the manufacturer.

The cellular antenna is a small and fairly fragile device. In some locations it may be necessary to take precautions against theft or vandalism (e.g., an antenna pole or site fencing). These precautions may add to overall site costs for materials and installation.

As mentioned earlier, Caltrans has a contractual agreement with Cellular One for cellular telephone service. It should be noted that the government service discount agreement dramatically reduces the ongoing cost of this type of CL. Also, cellular telephone equipment is priced substantially lower than other types of radio equipment. These two factors can make this CL very attractive for certain applications.

Caltrans has authorized a special liaison to oversee the purchase, installation and activation of cellular telephone service. Districts that are interested in using this type of CL should contact Mr. Dayle Goldsberry, Telecommunications Manager, Division of Maintenance,

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Office of Telecommunications at (916) 324-1964. Installation or removal of cellular telephone equipment may be performed by Caltrans district radio technicians or by contract.

The following table is typical of the pricing found in the major metropolitan areas of the state. The prices shown are the Caltrans contract prices from Cellular One. The equipment specified is that which is required for the Rain Bird Maxicom system.

Table 2.5: Typical Cellular Telephone Costs

ITEM	COST
Service establishment (per access number, per site)	$15.00 to $20.00
Cellular telephone equipment (Motorola cellular connection transceiver, antenna and power supply, per RSC)	$605.00 to $710.00
Cellular telephone equipment installation (per RSC)	$150.00 (Cellular One price)
Pole installation for antenna	Incurred only if additional antenna height is desired, cost is site specific, estimate on a case by case basis
Access charge (per month, per RSC)	$10.00 to $35.00
Usage rates (per minute, toll charges extra)	$0.20 to $0.39 for peak period, $0.12 to $0.23 for off-peak period
Equipment maintenance contract (per RSC)	$4.95 per month with a $50.00 deductible, plus an on site repair fee of $60.00 per hour and $0.30 per mile for each call out (Cellular One price)

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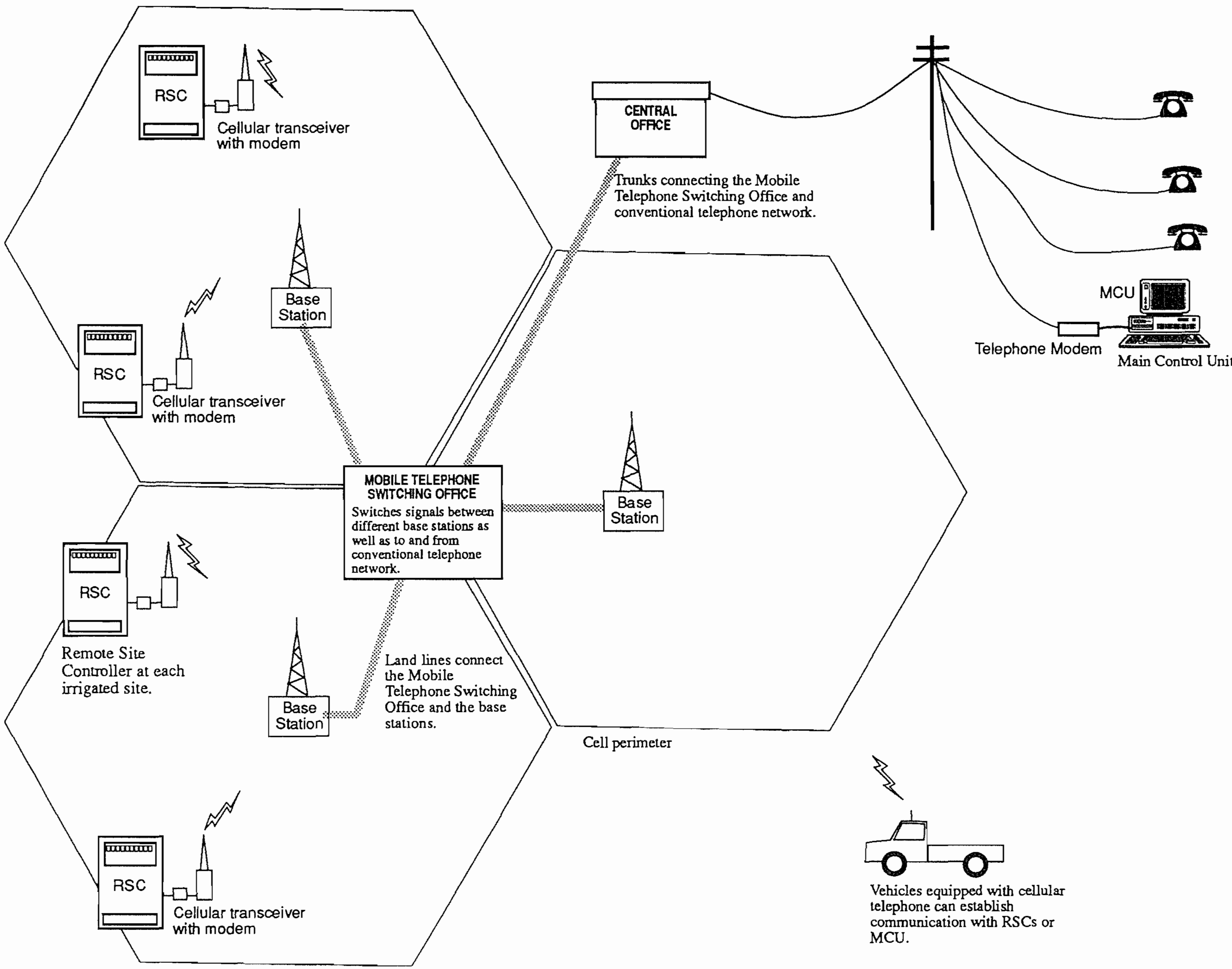

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Figure 2.4 Cellular Telephone Communication

2.10.5 Conventional Radio

Functional Description

In this section we survey the use of conventional point-to-point radio transmission for data communications. Radio is a wireless transmission method based on the principle that an alternating current produces electromagnetic radiation. This radiation propagates through the atmosphere at very near the speed of light. Because the medium is not bounded like a wire or a cable, the radio wave travels in multiple directions. Electromagnetic radiation exhibits the reflection, refraction, and interference phenomena associated with waves in general.

Radio transmissions are most naturally classified according to frequency. Transmission involves the modulation (encoding) of a source (baseband) signal on a higher radio frequency (RF) channel capable of propagating over a distance without the use of wire or cable. This discussion concentrates on data communications over Very High Frequency (VHF) and Ultra High Frequency (UHF), frequency modulated (FM) voice channels. These types of channels are used by all RIC system manufacturers supporting dedicated point-to-point or multipoint radio links. The VHF band extends from 30 MHz to 300 MHz, while the UHF band ranges from 300 MHz to 3000 MHz [3, p. 1].

The principal elements of RIC radio transmission systems are the modem, the transmitter, the receiver and the antenna. Often, the transmitter and receiver functions are incorporated in a single unit called a transceiver. Integrated transceiver/modem units are also available [4].

Data originating from the MCU, or an RSC, are first modulated into a voice-band signal by the modem. The modem has an RS-232 interface for the MCU's serial port and will support data rates of up to 4800 bps. At this point the modem output is similar to that of a private line data transmission channel modem. It is an analog signal occupying the voice band between 300 Hertz and 3000 Hertz. This signal is then fed into the audio input on the radio transmitter module.

The transmitter generates the RF carrier, modulates the carrier with the modem signal and then amplifies the modulated signal with an RF power amplifier before being coupled to the antenna. Typical available transmitter power output ranges from 1 to 5 watts [4].

The antenna serves as the interface between bounded and unbounded transmission. Bounded transmission takes place in the coaxial cable connecting the transceiver to the antenna, while unbounded transmission takes place in free space. Antennas are capable of transmitting and receiving with equal efficiency. To be efficient, their dimensions vary as a function of the operating frequency. As a reference, a 450 MHz radio wave has a wavelength of 0.67 meters. Therefore, a 450 MHz antenna has a size that is related to both the 0.67 meter wavelength and the physical design of the antenna. For comparison, a 30 MHz radio wave has a wavelength of 10 meters. If both antennas are of similar design, the 30 MHz antenna would be many times larger.

In general, there are two types of antennas, omnidirectional and directional. An omnidirectional antenna radiates RF energy (equally) in all directions. As a practical matter, it only radiates in a fairly uniform manner within the plane of the horizon. The radiation pattern can be thought of as a "doughnut" with the antenna at the center and the ring laying on the

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earth's surface. A directional antenna (sometimes called a beam antenna) radiates in a preferred direction. This directional quality can be extremely valuable when trying to increase the distance between two fixed sites or to reject interference from another station. Both types of antennas have numerous styles and designs for implementing their respective radiation patterns. For RIC applications, an omnidirectional antenna is often placed at the MCU so that RSC sites can be reached in all directions. The RSCs are then outfitted with directional antennas aimed at the MCU site. This configuration allows the system to take advantage of the stronger signal and interference rejection characteristics of directional antennas without confining RSC site placement.

VHF and UHF radio transmissions are considered to be "line of sight" (LOS). This means that there must be an unobstructed path between the transmitting antenna and the receiving antenna. In some situations it is not practical or possible to position the MCU transmitter in such a location that this would hold true. In these situations a radio repeater (sometimes just called a repeater) must be used to overcome the obstacles and establish a LOS path. A radio repeater is simply a receiver, a transmitter, some control circuitry and one or more antennas. As a practical matter, the signal received by the repeater is retransmitted on a different frequency. The signal through the repeater is not changed in any way except for the operating frequency translation and a power boost. Normally, the receive and transmit frequencies are chosen far apart to avoid interference to the receiver input by the transmitter output. The advantage of using a repeater is that it can be located on a high mountain top that has a LOS path to all the RSC locations. The repeater equipment can be owned, licensed and maintained by either the RIC system owner or by a separate business entity that specializes in repeater leasing.

The receiver accepts a signal from the receiving antenna, amplifies it, and demodulates it into a voice band signal. As with the voice band signal at the transmitter, it is similar to that from a private line data transmission channel. If the radio link is operating ideally, the signal is an exact reproduction of the one presented to the transmitter. In actuality, the received signal will be distorted by various transmission impairments that affect the radio channel, e.g., noise, co-channel interference, etc. The goal of a well designed radio telemetry system is to minimize these impairments and, where they still exist, to have a data transmission architecture that is as resilient as possible. The data signals must then be further demodulated by a modem. The output of the modem is then presented to the RSC or MCU as a serial (RS-232) digital signal.

All the RIC systems surveyed use a half duplex radio configuration. This allows each site to use only one antenna for both transmit and receive and involves less complicated electronics. It also limits the RSC or MCU from sending and receiving data simultaneously. This is usually not a problem since the amount of data transferred in a RIC system is small. For duplex operation the process of reception is complicated because the received signal power is very small when compared to that of the transmitter. To keep the transmitter from desensitizing the receiver, the transmit and receive frequencies must be far apart in the spectrum. Also, a tuned cavity filter arrangement and separate antennas are traditionally used to further isolate the two signals.

Conventional radio allows star topologies where the MCU uses an omnidirectional antenna and point-to-point connections are established directly with each RSC. A mountain top repeater also may be used to implement the star. In this situation the MCU would communicate with the RSCs through the repeater, the mountain top would then become the geographical hub of the star. Maximum radio link lengths of 20 to 25 miles were reported by some RIC system manufacturers. Some RIC systems allow a hard wired RSC bus to be linked by radio to the MCU.

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The operation of a RIC system over conventional radio is similar to that of a half duplex, multipoint, private line data transmission channel. The MCU computer is connected to the base station transceiver/modem either directly or through an interface unit. The exact function of this unit varies from system to system. In general, it performs data formatting before transmission to the field. Some systems include the modem in the interface unit. Others format the field data within the MCU computer and do not use separate interface hardware. Each RSC on the system is assigned a unique address. When the MCU needs to communicate with a particular field unit, it sends a packet or block of data containing the RSC's address and error checking codes. At the beginning of the data stream the transmitter is enabled (or "keyed"). Then the data block is transmitted to all the RSCs. The addressed RSC recognizes the data and checks the error code to determine if the data were received intact. If the code is correct, the RSC responds by keying its transmitter and sending an acknowledgement, an error checking code, and status data back to the MCU. All systems surveyed employ some sort of communications error checking.

Some systems offer a polling/answerback communications architecture, with the MCU in control of all data transfers. Other systems use an asynchronous communications architecture to enable the RSCs to initiate communications. Both designs were outlined in the private line section.

Reliability

Of the six Communication Links that are currently supported by RIC systems, conventional radio is probably the most difficult to implement from the standpoint of reliability. This does not mean that a radio system is inherently unreliable; it simply means that unforeseen problems are more likely to cause challenges for the system designer. The main factors that act in concert to cause difficulties are path uncertainties and radio spectrum congestion.

The subject of VHF/UHF radio propagation is extremely complicated and well beyond the scope of this report. Terrain, different air layer densities, and buildings create reflection, refraction, and diffraction phenomena that affect the propagation of radio waves. Other naturally occurring phenomena such as lightning, can cause severe noise interference to radio communications. While RIC systems use FM VHF and UHF radio systems to minimize these effects, they do not totally eliminate the problem. As a general rule, the shorter the distance between the RSCs and MCU the stronger the radio signal will be. With higher signal levels, the radio link is more noise immune and therefore more reliable. To assure reliable operation an engineering analysis of the proposed RIC system CL should be performed. As a State agency, Caltrans must work through the Department of General Services, Telecommunications Division for any analysis [17].

The radio spectrum is strictly regulated by the Federal Communications Commission (FCC) to prevent users from interfering with each other. The FCC requires all prospective licensees to participate in a local coordination process (as outlined in a later section) to try to prevent interference. Despite this regulation co-channel interference problems may still exist. Co-channel interference is the result of transmissions from other users of the same frequency being received by the RIC system radios. Terrain, antenna height, and other factors may cause this phenomenon to arise in unexpected situations, i.e., interference may occur from stations located well outside the normal range of the transceivers. This problem has a direct effect on system reliability because RSC and MCU data cannot be transferred in the presence of radio interference. It should be noted that co-channel interference is much more severe in urban areas where frequency usage is high.

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A system may be installed and have no problem with interference. Later, another operator may receive authorization to operate on the same channel. Even though the station is located outside the theoretical range of the RIC system, conditions may permit interference.

One key feature that dramatically affects system reliability is the ability of the transmission scheme to avoid, detect and recover from transmission errors. This determines how "error tolerant" or "robust" the transmission scheme is. The resiliency of the system architecture to communication errors is important to the successful operation of a RIC system. Some areas of the data transfer scheme that have an impact on error tolerance are: the type of error checking that is performed, the use of forward error correction, the sequence the system executes when communication fails on the first attempt, etc. An important method of avoiding an error condition is to have the transceivers monitor the radio channel before transmitting. If the channel is in use, i.e., an RF signal is present at the receiver, the unit will not transmit. It will wait until the channel is clear. This prevents the two stations from transmitting simultaneously and interfering with one another. Implementing automatic error avoidance features such as these greatly improve the probability of data transfer and increase overall system reliability.

Topology

All of the surveyed RIC conventional radio systems require a star topology. In non-repeatered systems the MCU is the hub of the star. Therefore, all RSC locations must be able to link directly with the MCU. For repeatered systems, the geographical hub of the star is located at the repeater site. With proper design, this arrangement allows for wider geographical placement of the RSCs.

Terrain Considerations

VHF and UHF radio links require an unobstructed path between transmitter and receiver. Considerable attention must be paid to terrain features such as mountains, buttes, hills, etc., to establish a clear path to all sites in the network. In urban areas, tall buildings tend to be the main problem in establishing a LOS path. Some cities have ordinances in place restricting the size and location of radio antennas.

Maintenance Requirements

The Department of General Services, Telecommunications Division, is responsible for all maintenance associated with conventional radio systems. The department establishes a maintenance schedule and provides technicians to perform the necessary work.

Licensing Requirements

As mentioned earlier, radio communication is regulated by the Federal Communications Commission (FCC). All RIC radio links require an FCC license before any transmissions can take place. As a non-academic state agency, Caltrans is required to obtain radio licenses through the Department of General Services, Telecommunications Division. Because highway

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maintenance requires the use of radio communications for day to day operations, a separate office within Caltrans has been established to act as a liaison with the Telecommunications Division. Any requests for licensing a RIC radio system should be directed to Mr. Dan Johnson, Division of Maintenance, Office of Telecommunications at (916) 445-5090 [17].

Most RIC conventional radio systems are intended to be licensed under the Private Land Mobile Radio Services, Non-voice and Other Specialized Operations [77]. It should be noted that data communication within this service is authorized as "secondary to voice." This means that RIC data telemetry must not interfere with land mobile voice communications. If interference does occur, voice transmissions have priority.

Special coordinating agencies exist to select frequencies for applicants to avoid interference between radio users. As an example, business radio service is coordinated by the National Association of Business and Educational Radio (NABER), while Highway Maintenance service is coordinated by the American Association of State Highway and Transportation Officials (AASHTO) for bands below 800 MHz, and by the Associated Public Safety Communications Officers (APCO) for the 800 MHz band [5, p 239]. For RIC applications, the Caltrans Office of Telecommunications collaborates with AASHTO and APCO to obtain available conventional radio frequencies.

Successful frequency coordination is a difficult process. Often times, frequencies selected experience interference problems not predicted during the licensing process. In many urban areas, the conventional radio spectrum is so heavily used that obtaining a frequency for operation is not possible.

The Department of General Services, Telecommunications Division, requires an initial engineering study to determine the feasibility of using conventional radio for a particular application. If the study concludes that the coordinated frequencies will meet the project's operational needs, the licensing process continues. FCC Form 574, along with supplemental frequency coordination information, and the appropriate fee are submitted to the FCC. The FCC has the final approval decision power to issue the license [5, p 238].

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Costs

Table 2.6: Typical Conventional Radio Costs

ITEM	COST
Initial engineering study required by Communications Division (per system)	$3500.00 to $5500.00 (price is based on an hourly rate, cost will vary on a case by case basis)
Frequency coordination fee	Included in initial engineering study
License fee	Included in initial engineering study
Transceiver, modem, power supply, cables and antenna	$1000.00 to $2600.00 (per RSC), $1100.00 to $4200.00 (for MCU), radio equipment is specified by the RIC system manufacturer
Radio equipment installation	$100.00 to $225.00 (per RSC), $100.00 to $475.00 (for MCU), installation is usually included in RIC system price
Maintenance fee required by Communications Division	Price is based on an hourly rate until a system history is established, a fixed rate is then calculated, cost will vary on a case by case basis

Interference problems may cause additional costs. There is no way to accurately predict the cost that may be incurred.

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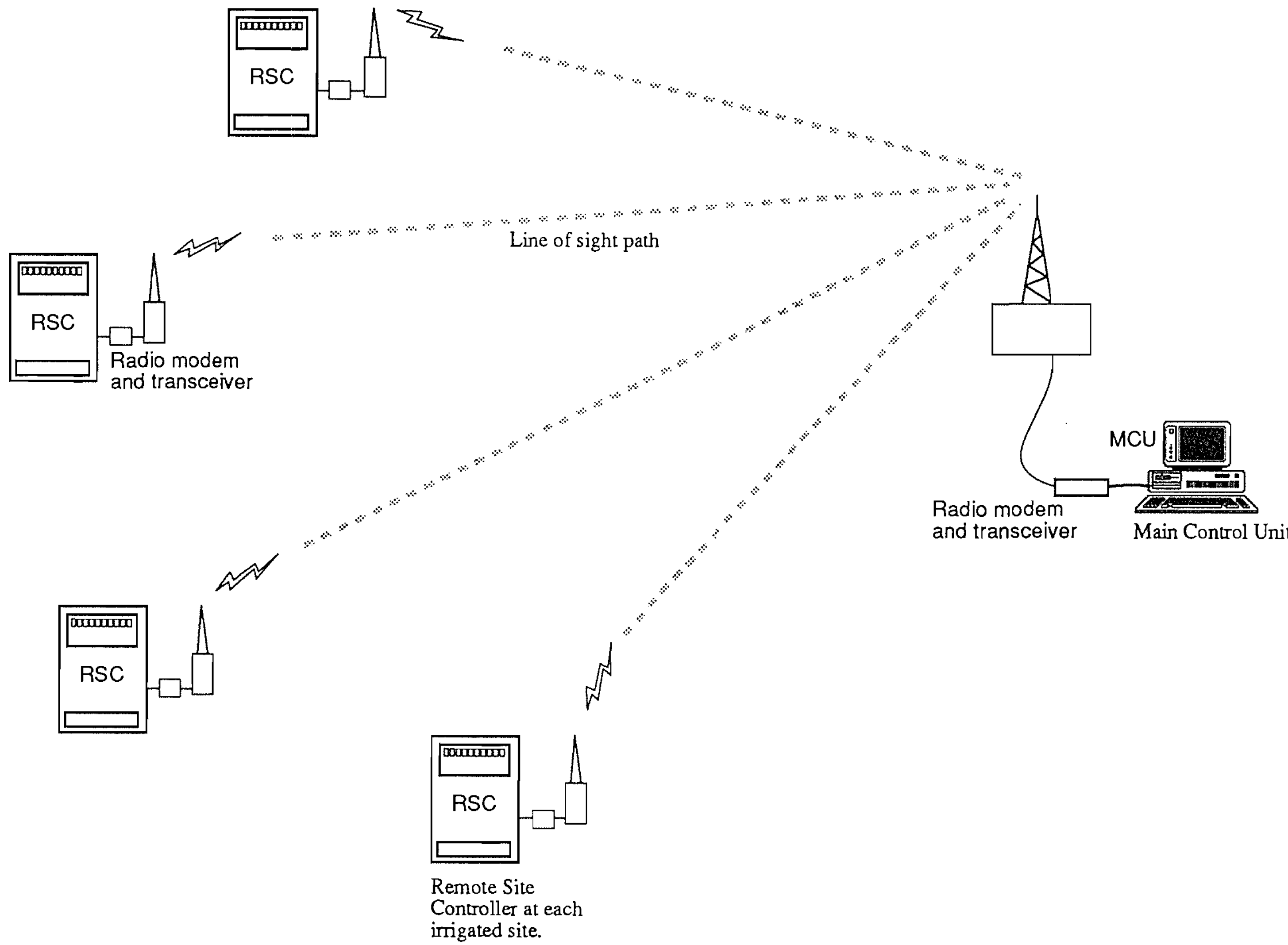

Figure 2.5 Conventional Radio Communication (without Repeater)

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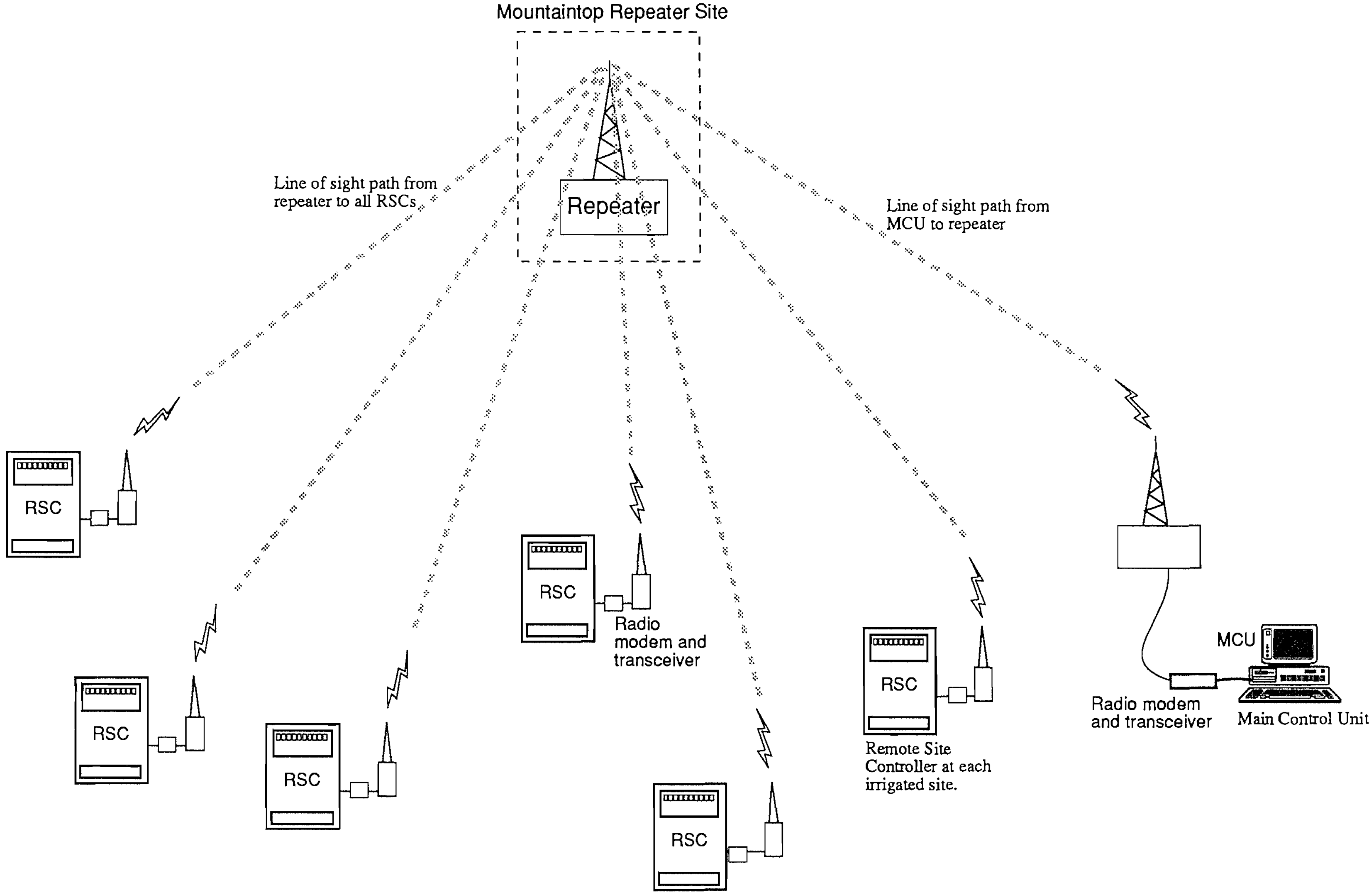

Figure 2.6 Conventional Radio Communication (with Repeater)

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2.10.6 Trunked Radio

Functional Description

In this section we survey the use of trunked radio systems for data communications over voice channels. Trunked radio uses multiple radio frequencies to allocate channels dynamically when a transmitter is activated. This process is similar to the way that, for example, intra-LATA trunks are used in dial telephone communications. This is in contrast to conventional radio systems, where a dedicated single channel is used for transmission between two stations. Trunked radio systems are designed primarily for voice communications in dispatch-center type of applications [9, p. 1]. One of the most important advantages of trunking is that it reduces blocking for a given amount of traffic as compared to conventional radio [11, p 2-1].

Trunked radio channels are allocated in the 800 MHz and 900 MHz bands [11, p 1-3]. There is no system signaling standard for trunked radio operation. This discussion focuses on the Motorola Smartnet and the E.F. Johnson LTR systems because they comprise the overwhelming majority of trunked systems within California. They differ significantly in the way that signaling and supervision are performed, and in their overall support of data communications.

The basic common elements of a trunked radio system are mobile stations, the dispatch station [11, p.3-5] and the repeaters. Communications between mobile stations and the control station are performed via the repeaters, which are allocated dynamically to provide trunks for such communications. Each system has from 5 to 20 two-way voice channels [10, p. 2] and one repeater per channel.

A RIC station has a transceiver, an antenna, and a data modem that is specifically designed for radio communications. The data modem function may or may not be implemented as a separate unit. Each transceiver is assigned an ID number by the system operator [10, p. 2]. In the idle state, the receiver output is muted and the transmitter is inactive. To transmit data the RIC station must activate (key) the transmitter. Similarly, for the RIC station to receive data the receiver must be unmuted. Muting and unmuting are performed automatically by the transceiver when it receives the correct control codes [10, p. 2].

Stations can be grouped and subgrouped to implement different and very diverse communication hierarchies [9, p. 1; 11, p. 6-1]. Groups and subgroups are also assigned ID numbers that are stored in the transceiver's memory [10, p. 2; 11 p. 5-1]. Groups can be assigned different priorities, for example, to allow public safety communications to have higher priority during emergencies [9, p. 8].

For RIC applications the mobile stations would correspond to the RSCs and, possibly, landscape maintenance crews. The dispatch station is fixed [11, p.2-3] and would correspond to the MCU. Some stations are capable of selecting groups with which to communicate (the dispatch station, for example), while others have a single group assigned to them. For a standard RIC system implementation, the grouping is comprised of the MCU and the RSCs to be controlled. All stations within the RIC group have equal priorities.

A repeater consists of a transmitter, a receiver, control circuitry and an antenna. Each repeater is designed for single channel operation. The repeater retransmits the RF signal

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detected by its receiver on the repeater's assigned channel. The control circuitry implements the control protocol used to coordinate the trunking process. All trunking repeaters in the system are usually housed at a single site [5, p. 76]. In some configurations, repeaters share a single antenna by means of combiners.

Protocol for making a connection begins via an initialization channel. The initialization channel is implemented differently in each of the systems surveyed. In general, the process is as follows [11, p. 2-3; 10, p. 6]:

The initiating station sends a call request over the initialization channel indicating its ID and the target group and then becomes silent. The system checks for an available repeater and, if one is found, a channel assignment message is transmitted indicating the target group and the repeater to be used. Otherwise, a busy message is sent to the initiating station and a busy tone is generated at the transceiver. When the target stations detect the channel assignment message, they switch to the specified channel and unmute their receivers. When the initiating station receives the channel assignment message, the transmitter is activated and communication proceeds.

The Smartnet system dedicates one of its repeaters as the initialization channel (called the control channel) to transmit and receive control data between the stations and the Central Site Controller (CSC) [10, p. 2]. The CSC mediates all call requests, channel assignments, and performs other signaling and supervision functions. Call requests and channel assignments are made over the control channel. During a call, supervision takes place over the voice channel itself. This process is similar to the one used in cellular telephone communications. The CSC also assigns a different repeater as the control channel every 24 hours. Repeaters in the system are used as voice channels when they are not the designated control channel.

In contrast, the LTR system performs signaling and supervision functions over the voice channels themselves (i.e., there is an initialization subchannel in the voice channels) [11, p. 2-3]. Each station is assigned to a "home repeater," which mediates all call requests and channel assignments for all stations assigned to it or, if it is busy, directs them to another repeater. The repeaters are linked by a local data bus to coordinate trunking in a distributed fashion, i.e., they collectively constitute the equivalent of the Smartnet CSC. When a station requests a trunk it is assigned the first available repeater. This repeater is not necessarily the home repeater. During normal operation the channel assignment message causes the target stations to unmute their receivers and the initiating station to activate its transmitter. No further signaling is provided to indicate that the initiating station has acquired the assigned channel, or to indicate that transmission is still taking place. The initiating station marks the end of transmission by sending a special code when its transmitter is deactivated. Then, the assigned channel is released and the target stations mute their receivers.

There are two types of channel assignments [10, p. 4]. The first one is called "Message Trunking" in which the channel assignment is preserved for the duration of a conversation. This means that several transmissions may occur before the channel is reassigned. In this way, for example, the MCU might poll an RSC and receive its response while using the same trunk. In one possible implementation, the channel is considered free for reassignment when it is idle for a predetermined period of time, otherwise, it remains trunked while transmissions take place.

The second channel assignment type is called "Transmission Trunking" in which the channel assignment lasts only for the duration of a single transmission. Subsequent transmissions require contention for a new channel, which could introduce unacceptable delays during periods of heavy traffic.

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Smartnet supports both types of trunking by providing a repeater drop-out parameter that can be modified by the system operator [10, p. 4]. This parameter indicates the length of time the CSC allows the voice channel to be idle before deciding to release the assigned repeater. In contrast, LTR supports transmission trunking only. An end of transmission code is sent by the transceiver when its transmitter is deactivated. Upon receipt of this code, the trunk repeater is released [11, p. 2-6].

Data communications support differs in both systems as well. The LTR system offers Data Interface Modem units with RS-232 interfaces [11, p. 3-7]. Both the stations and the trunk repeaters must be equipped with modems. The system operator must restrict the pool of repeaters to be used for trunking the data stations to those equipped with modems. It should be noted that there are modems available from third party manufacturers that will operate on an LTR system. These units do not need a separate modem at the repeater. Currently, at least one RIC manufacturer uses this type of modem for their system.

Smartnet does not offer separate modem units, in other words, Smartnet equipment capable of data transmission incorporate built-in modems. Two types of data communications are supported: burst messages and text messages [9, p. 10]. Burst messages are sent over the control channel and, consequently, can be sent without waiting for trunking and even when all voice repeaters are busy. However, their length must be restricted in order to not interrupt normal control channel operations. Text messages are sent over voice channels and do not have restricted lengths. By using a GMS-500 message switch computer, Smartnet can exchange data between data terminal stations and an MDS-500 dispatch computer or other remote computers. None of the RIC systems surveyed use this feature. As with the LTR system, there are modems available from third party manufacturers that will operate on a Smartnet system. Motorola's MIR 5000 RIC system uses its own proprietary Field Interface Unit (FIU) as a combination data formatter and specialized modem for trunked radio applications.

Trunked radio systems can provide service for an area of about 50 miles from the repeater site [9, p. 5]. There are several ways to extend the area of coverage. Both Motorola and E.F. Johnson systems provide interfaces to the Public Switched Telephone Network. Several Smartnet sites may be linked by microwave to provide wide area coverage [9, p. 5]. One of the sites is designated as the prime site and its CSC coordinates operations with the remote site CSCs over the microwave link. The Automatic Multiple Area Switching feature enables a single Smartnet system to provide wide area coverage by splitting the system channels to implement multiple subsystems [9, p. 6].

Trunked radio systems may be for private use or may provide services for the general public. Private trunked radio systems are owned, licensed, installed and maintained for use by a single entity. Although they incur the full responsibility of FCC licensing and subsequent loading requirements, these systems can be tailored for very custom applications. In some areas, Caltrans is in the process of installing private trunked systems for highway maintenance. This is part of the Caltrans state wide 800 MHz mobile radio conversion. Concerns over system loading during an emergency have prompted the Office of Telecommunications to limit system utilization to voice applications only [17]. Because of this, it is not available for use in implementing a RIC system.

Companies providing trunked radio service to the general public are called Specialized Mobile Radio Systems (SMRS) [11, p. 1-1]. SMRS take advantage of the grouping capabilities of trunked radio systems to satisfy the demands of many different subscribers. For RIC applications, the MCU and the associated RSCs are assigned to the same "talk group" on the SMR system. A monthly fee is paid to the SMR provider for use of the system. Some SMR services provide exclusive use of a group of repeaters for users with high reliability

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requirements. Because of the limitations placed on the use of any Caltrans trunked radio system for a RIC application, service through an SMR is the only option available.

Reliability

The reliability of trunked radio systems is adequate for RIC applications. Quality coverage is currently available in all major metropolitan areas and most medium sized cities.

Being a radio based communication link, quality of service tests should be conducted at every planned RSC location. All tests should be performed before a final decision to implement this type of CL is made. Most SMR service providers have detailed coverage information available to prospective users. Generally, if the trunked radio link is initially acceptable it will remain so.

It should be noted that during heavy traffic periods (normal or emergency) contention for system access can result in considerable delays and interruptions. This is especially true if the RIC system talk group is assigned a lower priority than other users.

Topology

Due to the nature of a trunked radio system, RIC designs using this type of CL require a star topology. The geographical hub of the star is located at the repeater site. For RIC systems that cover a large area it is possible to use extensive grouping capabilities and operate through two separate trunked radio systems. This type of arrangement would implement a dual star topology, with the hub of each star located at each repeater site.

Terrain Considerations

Since trunked radio systems utilize UHF radio, an unobstructed Line of Sight (LOS) path to the repeater site is necessary. Considerable attention must be paid to terrain features such as mountains, buttes, hills, etc. to establish a clear path to all sites in the network. It should be noted that situations may arise where there is no single mountain top location which has a LOS path to all RSC sites. This adds considerable complexity to the design of the trunked radio CL. If the MCU location has a LOS path to two trunked radio systems at separate mountain top locations and the combination of the coverage areas will reach all RSC sites, then a hybrid arrangement between the two trunked radio systems can be implemented. Currently only the Motorola MIR 5000 system can accommodate this situation. For applications where the MCU does not have an LOS path to two trunked radio systems and one repeater site will not provide adequate coverage, an alternative CL should be considered.

Maintenance Requirements

The end user has the responsibility of maintaining all customer owned trunked radio equipment. In most applications, the equipment is sold as part of the RIC system. Therefore, Caltrans is required to provide for the repair of any malfunctioning transceiver. Most SMR service providers offer a service contract for equipment repair after the warranty period expires.

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Maintenance contracts may be purchased through normal contracting channels on a district by district basis.

Licensing Requirements

All end users of an SMR system must be licensed by the FCC [8] but do not have to participate in frequency coordination [24]. After service from an SMR provider is purchased, the appropriate FCC forms must be completed. The approval of the end user license is immediate and use of the system may commence. Operational fixed stations (e.g., RSCs) are permitted to transmit data on a secondary basis to voice communications [25].

Costs

The price of SMR service varies throughout the state. The primary factor affecting price is the level of competition in a given geographic location. For RIC applications, systems which offer this type of CL usually have specific trunked radio equipment that is recommended by the manufacturer.

Subscription costs typically include a fee for an FCC end user license, the cost of programming the user's grouping, a monthly fee for the use of the system, a fee for activation of service, and the purchase of the necessary station equipment (e.g., transceivers, antennas, etc.).

Caltrans has authorized a special liaison to oversee the purchase, installation and activation of trunked radio service through an SMR. Districts that are interested in using this type of CL should contact Mr. John Schmidt or Mr. Ron De Leon, Division of Maintenance, Office of Telecommunications, Special Projects Branch at (916) 327-6210 or (916) 324-8954, respectively. Installation or removal of trunked radio equipment may be performed by contract.

The following table is typical of the pricing found in the major metropolitan areas of the state.

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Table 2.7: Typical Trunked Radio Costs

ITEM	COST
Service activation (per system)	$100.00 to $150.00
End user license fee	$35.00
Trunked radio equipment (Transceiver, antenna, and power supply, per RSC and for MCU)	$970.00 to $2850.00
Trunked radio equipment installation	$140.00 to $225.00 (per RSC) $250.00 to $475.00 (for MCU)
Repeater rental (per RSC and for MCU)	$13.00 to $20.00 (per month), 75 minutes per month usage, $0.30 for each additional minute *
Equipment maintenance contract	4.5% of radio equipment purchase price, per month

* For purchases of the Motorola MIR 5000 system, Motorola will provide SMR service as well as the RIC system. The cost of SMR service in this situation is substantially lower. The repeater rental is from $3.00 to $5.00 per RSC and for the MCU. Also, there is no per minute usage fee.

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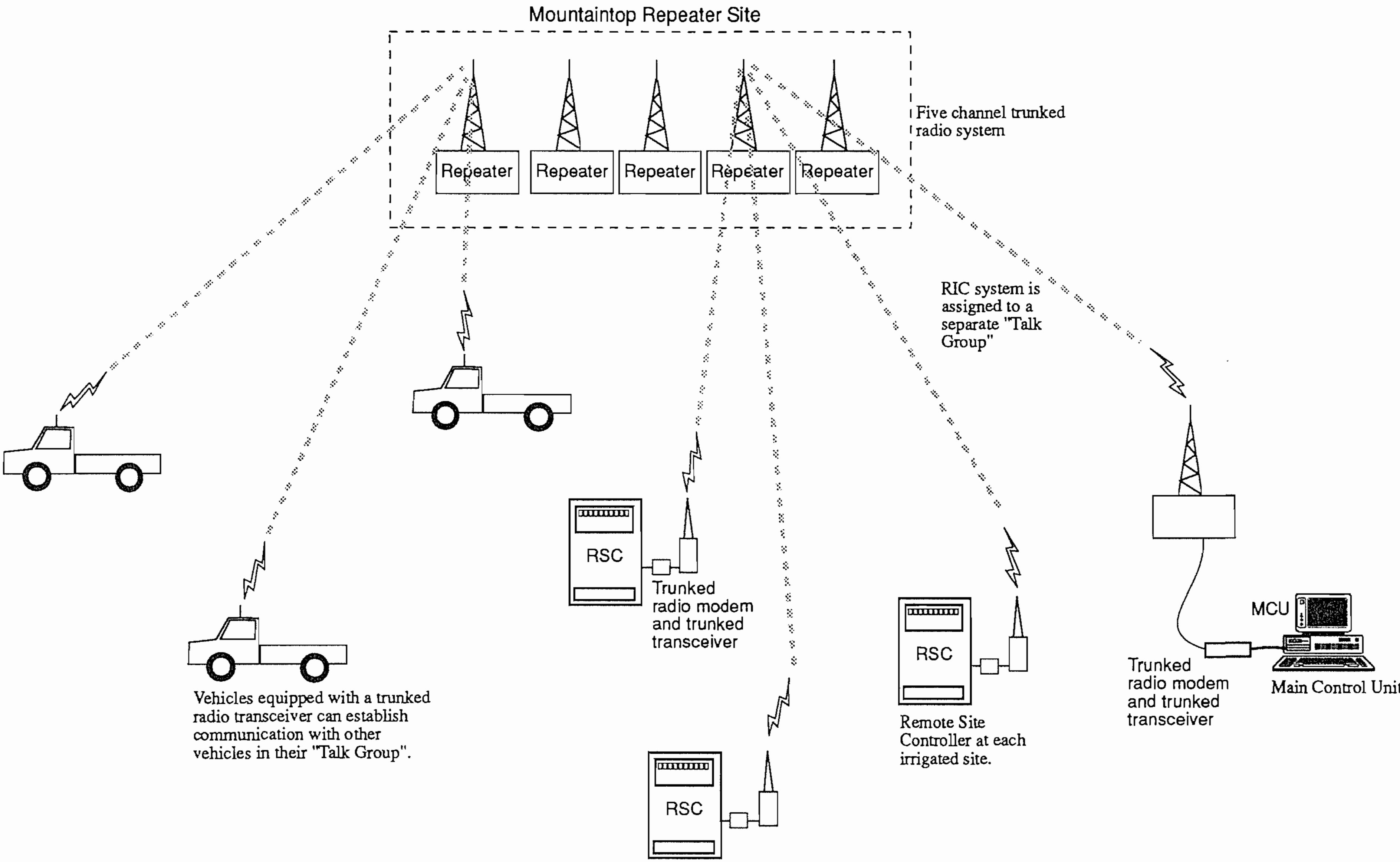

Figure 2.7 Trunked Radio Communication

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2.11 Selection Criteria

It is important to realize that no single type of Communication Link (CL) will meet the needs of the many possible RIC applications in all Caltrans districts. The system designer should view the different CL technologies as tools in a tool box. No one tool is able to perform all functions adequately. The job of the system designer is to evaluate the particular application and choose the tools which will do the best job of communicating with the Remote Site Controllers (RSCs) at an acceptable cost. Certain applications may arise where it is necessary to use more than one type of CL on the same system. There are several RIC systems that will support this kind of hybrid arrangement.

The six CL technologies fall into two groups, wireline based (hard wire, dial telephone and private line telephone) and radio based (cellular telephone, conventional radio and trunked radio). Each group has unique characteristics and inherent advantages and disadvantages.

In general, wireline systems are much more difficult to install, and therefore are more costly, than radio systems. This is due to several factors such as obtaining easements for cable installation, obstacles that impede trenching in retrofit applications, difficulty in expanding an existing RIC system to more RSC locations, etc. The system designer must carefully consider the effects of future highway expansion when deciding on the location of the cable route. An advantage to wireline is that if the system is installed properly, it will usually remain operational with very few problems for many years. Also, for hard wire systems, there are no usage fees and consequently very few ongoing costs. For many urban projects wireline is the only viable option because of radio congestion. For example, District 7 has a RIC project under construction at the I-710 and State Route 60 interchange. The system designer chose to use a Dial telephone CL because no conventional radio frequencies were available and the project site did not have a Line Of Sight (LOS) path to a mountain top repeater necessary to utilize trunked radio. It should be noted that in many urban areas a connection point to the Public Switched Telephone Network (PSTN) is located only a few feet from the RSC sites and therefore a telephone based CL (dial or private line) may be appropriate.

Radio based systems have the advantage of not having to physically connect a cable to each RSC location. This greatly simplifies the installation of hardware associated with the RIC system. Of the three radio based CLs, conventional radio involves the most uncertainty as to cost and availability. In most urban areas this CL is not a viable option due to frequency congestion. For some regions with a low population density that can be served by direct transmission or through a single repeater, this may be an appropriate CL. Both cellular telephone and trunked radio have the most promise for being an appropriate CL for most applications. Being radio based, they are easy to install at the RSC sites. The primary advantage of these CLs is that the coverage areas of the various systems are well known, and this information can be obtained in advance of committing to a particular design. Also, sites can be pretested with the actual equipment and systems to be used in the permanent installation. It is an important advantage to be able to accurately predict whether the CL will work for all sites and in determining all costs of service.

Trunked radio has the advantage of offering access to all RSC sites simultaneously. However, it is limited to serving sites with an LOS path to a single mountaintop location. In areas with very mountainous terrain, such as coastal regions, this limitation can severely restrict the size and expandability of a RIC system.

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Cellular telephone provides a network that is designed to service the highway user. Since Caltrans RIC projects are also located along major highways, the use of this technology may be advantageous in some locations. Additionally, the network is not limited by traditional connectivity boundaries, i.e., the CL can offer communication with sites one mile away or one hundred miles away, the only difference to the user being the connection cost. As long as an RSC site is served by a cellular network or the PSTN, it can be quickly linked to the system MCU. The major drawback to this type of CL is that RSCs can only be accessed serially (one at a time). For a large RIC system, the time involved in connecting and disconnecting each site for system wide commands is substantial.

Another way to group the six communication links is by type of access. Dial telephone and cellular telephone both have a serial access structure. As was explained earlier, this means the RSCs can only be accessed a single site at a time. Hard wire, private line telephone, conventional radio and trunked radio all allow simultaneous access to the RSCs. The access issue needs to be considered early in the RIC design process. The ability to access all sites quickly for global commands is one of the issues that puts a practical limit on the size of the RIC system.

For a specific RIC application, the communication link should be chosen using a conservative design approach. The designer should examine the CLs which are available at the project location. Any plans for future expansion of the system should be included in the examination. An analysis of the installation and ongoing costs associated with each viable CL should then be performed. Finally, the designer must make a determination as to which CL will yield the best possible performance at an acceptable cost.

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CHAPTER 3

EXISTING REMOTE IRRIGATION CONTROL SYSTEMS

3.1 Prior Work

This section presents an overview of prior work in the fields of telemetry and remote control leading up to current Remote Irrigation Control (RIC) technology.

Remote control systems originated as an evolution of telemetering or telemetry systems designed to perform remote measurement of physical variables. The first applications of telemetry technology date back to the early 1800s and include the detonation of mines in Russia, the analysis of cannon-ball trajectories, and meteorological measurements at Mont Blanc [48, p.1-3]. The measuring equipment in these systems was dedicated to single, fixed tasks. The capabilities of these systems were later augmented to perform control of actuators at the remote site. Many early remote control systems were used in military applications, especially the guidance of experimental aircraft and missiles.

Subsequently, industrial and commercial applications started to appear. Systems known as Supervisory Control and Data Acquisition (SCADA) systems are commonly used today to monitor and control the delivery of commodities in industries such as electric utilities [34] [35] [36] [39] [43], oil and gas [29] [31] [46] [47], and water distribution and treatment [33] [41]. In these systems the field units are called Remote Terminal Units (RTUs).

RIC systems have evolved alongside telemetry and remote control systems designed for agricultural irrigation and research. The wide spread use of these systems has been made possible by the advent of microprocessor technology. Cromer et al. [26] used radio telemetry to link a distributed microprocessor-based control system that used tensiometers to measure soil moisture. Bradbury et al. [27] used a hard wire system to control surge irrigation of a 160 acre field with a Commodore VIC-20. This system superimposed high-frequency signals over the 24-VAC lines used to power the solenoids. Dedrick et al. [49] modified a time-based controller to provide volume-based control of a surface irrigation system. Kidwell [44] used an Apple II computer, radio telemetry, and volumetric sensors to control the actuation of gates in a flood irrigation system in Arizona. King et al. [45] designed and tested a semi-automatic irrigation gate controller for use in graded border and border ditch irrigation. Cockermam et al. [40] used infrared telemetry for the remote acquisition of meteorological data at the University of California Riverside's Agricultural Experiment Station.

Electromechanical controllers provided the earliest form of time based irrigation programming for turf applications. Centralized control was made possible when microcomputers and telephone modems became affordable. Solar Wind Systems' System 390, introduced in the mid 1970s, is the first known commercial RIC system to appear on the US market.

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3.2 Water Conservation Utilizing RIC Systems

This section deals with water conservation support in Remote Irrigation Control (RIC) systems. Water conservation is especially necessary to meet rising water use in semi-arid areas with recurring drought conditions like California. In particular, this section focuses on using RIC systems for irrigation optimization, environmental feedback sources and water recycling in highway landscape applications.

3.2.1 Irrigation Optimization

The primary purpose of irrigation is to deliver water to the soil to provide the moisture necessary for plant sustenance and growth [28, p. 4]. Other purposes include plant cooling, frost prevention, washing out or diluting salts, fertilizer application, etc.

The soil can be modeled as a water reservoir having inputs and outputs. Irrigation water is used to supplement the moisture provided naturally to the soil by rainfall, dew, flood water and ground water as part of the hydrologic cycle. Water input from these sources is unpredictable and varies dynamically according to time and geographical location.

Water losses include transpiration, evaporation, percolation and runoff [55, p. 198]. Transpiration occurs when water absorbed by the plant roots leaves as vapor, mostly through the leaves. Evaporation refers to unabsorbed water losses from the soil surface, water surfaces, and plant surfaces. Evapotranspiration (ET), the combined quantity of evaporation and transpiration, is a measure of the plant's consumptive use of water. It is usually given in inches or millimeters. Variations of the Penman equation [57, p.119] are commonly used to calculate ET from solar radiation, air temperature, wind speed and vapor pressure data values. Reference Evapotranspiration (ETo) is a measure of ET for a reference crop; ET for an arbitrary crop is obtained by multiplying ETo times a crop coefficient. Percolation refers to the water that passes through the plant root zone and drains into the water table without being absorbed by the plant. Runoff refers to water lost when applied after the soil's infiltration rate has been exceeded. Again, water losses vary dynamically with time and geographical location.

Plant requirements, soil characteristics and weather conditions are the predominant factors in scheduling irrigation. In terms of water conservation, irrigation optimization refers to the minimization of irrigation water use to keep the soil moisture level necessary to meet the plant requirements. The determination of the necessary constraints to optimize irrigation is a very complicated process.

Starting with a situation where the landscape vegetation already has adequate soil moisture, two steps are involved in irrigation optimization. First, the net water loss for a given period must be estimated as accurately as possible to determine the amount of water that must be supplied. This involves subtracting the water losses from water supplied by other sources, a process sometimes compared to balancing a checking account and described by the water-balance equation [56, p. 63]. In practical terms computing irrigation water demand requires acquiring and processing environmental feedback data at a rate that can keep up with meteorological changes. For a non-RIC system having widely scattered remote sites, frequent manual data acquisition and irrigation adjustments are not practical.

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Second, the irrigation water must be delivered with a minimum amount of loss during delivery. Losses due to evaporation can be minimized by scheduling irrigation when evaporation is minimal and by suspending irrigation when weather conditions increase evaporation losses. Losses due to exceeding the soil infiltration rate (runoff) can be minimized by supplying the water in short cycles separated by soak periods. Losses due to main line breaks, broken sprinklers, stuck valves, etc. can be minimized with the use of flow monitoring equipment or moisture sensing coupled with sensor-based programming. Again, the process is labor intensive and amenable to automation.

In the absence of automated data acquisition and remote irrigation control, often the most practical solution is to schedule irrigation to meet the highest anticipated water demand. In cases where the same point of delivery is used to irrigate a variety of vegetation the problem is compounded because the minimum scheduled irrigation must match the requirements of the neediest plant. Also, detection of alarm conditions can involve significant delays before corrective action is taken.

Many RIC features can be used to achieve irrigation optimization. The most important contribution of RIC systems to water conservation is the ability to enable "closed-loop" irrigation control based on environmental data acquisition. This mode of control can save water by tracking water demand more closely, monitoring the delivery of water and providing quick response to water delivery system malfunctions. The amount of water saved is difficult to predict and varies from case to case depending on how efficient the existing irrigation practices already are. As explained before, some over-irrigation always occurs as a consequence of sharing a single point of delivery among many types of plants. RIC retrofits do not address this type of over-irrigation.

At the very minimum, RIC systems enable a human operator to quickly dispatch irrigation adjustment commands (such as water budget factor changes, rain holds, etc.) to the remote site controllers (RSCs). At the other side of the spectrum, RIC systems can provide environments for fully automated operation where the system acquires and processes the feedback data and then formulates, issues and monitors irrigation adjustment commands and alarm responses. Realistically, considerable operator supervision is still required to manage large systems even with the most full-featured RIC systems.

One of the main cost factors incurred by closing the control loop stems from the cost of the sensing equipment itself. Adequate sampling of environmental data for sites distributed over large geographical areas can require a large number of sensors and can quickly become very expensive. One way to cope with this problem, for example, is to use environmental adjustment factors to adapt measurements acquired from a single source to vegetation at different sites. In some cases historical ET data can be used successfully to schedule irrigation.

3.2.2 Environmental Feedback

This sections presents typical components used to provide environmental feedback in RIC systems. The basic operation of weather stations, the California Irrigation Management Information System (CIMIS), and moisture sensors is explained.

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3.2.2.1 Weather Stations

Weather stations are used to acquire various meteorological data. The de facto standard in the field is the Campbell Scientific Inc. 012 weather station. This weather station is the one used by all RIC systems providing weather station support.

The CSI 012 weather station consists of several sensors, a measurement and control module, a power supply, communications equipment and supporting software. Power options include battery operation, AC power and solar power.

Standard sensors are provided to measure air temperature, wind velocity, solar radiation, relative humidity and rainfall. ET values can be computed from these measurements. Wind speed is measured using voltage, photo-chopped, switch closure or magnetic pulse anemometers. Wind direction is measured with a precision potentiometer wind vane. Rainfall is measured by a tipping bucket rain gage. Solar radiation is measured by a silicon cell or thermopile pyranometer. Temperature and relative humidity are measured by a temperature & RH probe. Additional sensors are available to customize designs for different applications.

The CR10 Measurement and Control Module, sometimes called a datalogger, is the heart of the 012 weather station. This programmable module provides sensor measurement, timekeeping, data reduction, data/program storage and communication functions. An optional keyboard/display unit (CR10KD) can be used for manual operation in the field. The standard configuration provides enough memory to hold 29,900 data points. Up to eight additional removable storage modules (each capable of storing 96,000 or 358,000 data points) may be used to increase data storage capacity. Also, additional peripherals may be used to increase input, output and timing capabilities.

The CR10's programming language has approximately 90 types of instructions. Input/output instructions are used to communicate with external devices and to specify sensor measurements. Processing instructions support data reduction, e.g., unit conversions, etc. Output processing instructions compute statistics (averages and standard deviations) and other functions on measured data. Program control instructions are used to define the sequence of execution of the program. Programming can be done at the field with a CR10KD unit or remotely from a personal computer. The CR10's programming features allow for flexible meteorological data acquisition. The standard program provides hourly and daily reports of the average values read by the standard sensors, the daily reports include minima and maxima values as well.

Several Communication Links (CLs) are available for remote operation using two-way communications. These links include RS-232, dial telephone, cellular telephone, coaxial cable, 4-wire twisted pair, and conventional radio. The RS-232 link has a maximum range of 100 feet. The 4-wire twisted pair link uses short haul modems for a maximum range of 6.5 miles. The coaxial cable link uses multidrop modems to communicate with up to 200 dataloggers on a segment of cable up to 3 miles long.

Special software enables programming, data processing and real-time data monitoring from a personal computer. ET values are not provided directly by the weather station's standard program but can be calculated from the standard sensor measurements it provides. For example, Aqua Engineering's Weather_2, a water management software package used by some RIC systems, provides ET data calculated from CSI 012 weather station data.

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Manufacturer's recommended maintenance procedures are as follows. The rain gage must be checked every 6 to 12 months and readjusted if necessary. The pyranometer must be inspected and cleaned every two to three months. The anemometer and wind vane bearings must be inspected once a year. The temperature and relative humidity probe require monthly inspections to check that its radiation shield is free from debris and that the sensor screen is clean. Reportedly, smoggy environments shorten the life expectancy of this probe to approximately one year. The calibration of the probe must be checked once a year. Weather station maintenance service contracts are commonly available from RIC system distributors.

The price for a battery-operated model 012 weather station equipped with standard sensors and a short haul communications package plus datalogger support software is about $5,000.00. Typical replacement costs for the standard sensors range from $240.00 to $470.00 per sensor.

3.2.2.2 CIMIS

The California Irrigation Management Information System (CIMIS) is a network of weather stations located throughout the state of California. CIMIS is operated by the California Department of Water Resources (DWR) to increase the number of agricultural growers and turf managers using ET data to schedule irrigation. A "login ID" and a password must be obtained from DWR to access the CIMIS computer, the service is free of charge. For more information contact Holly Sheradin, CIMIS Program Manager, at (916) 322-6820.

Precipitation, soil and air temperature, solar radiation, relative humidity, wind velocity, dew point and other meteorological data are transmitted nightly by the weather stations to the CIMIS computer in Sacramento. This computer can be accessed remotely via telephone to examine the system's weather data. The CIMIS computer presents a mainframe style, menu driven interface for interactive use.

Daily and hourly weather data reports are available for nearly 80 weather stations in the state. Data can be requested by weather station or by weather station sensor. No real-time monitoring is possible because data are posted once a day only. ETo values provided by CIMIS are calculated by a modified version of Penman's equation as explained under item 13 of the main menu. Data can be requested in comma-delimited ASCII format for integration into spreadsheets, databases, and other software.

Particularly, some RIC systems now support or plan to support automatic retrieval of CIMIS ETo data by the Main Control Unit (MCU). This method of implementing ET driven irrigation is one of the least expensive. However, CIMIS users do not have much influence on weather station location assignments and maintenance response.

3.2.2.5 Moisture Sensors

Soil moisture measurements are very important in irrigation scheduling. Measurement techniques range from subjective "eyeball" assessments to sophisticated radiation-based techniques. The gravimetric method [56, p. 62], one of earlier standard measurement methods, involves taking soil samples to a laboratory, where they are dried in an oven. The difference in weight before and after drying indicates water content.

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One of the most accurate and most widely used methods in research environments today is the neutron method [57, p. 63]. In this method a neutron probe emits fast neutrons into the ground, where they are slowed down by water molecules. A radioactive counter is used to measure the relative number of neutrons slowed by the soil water, which then gives an indication of water content. This method is very fast, non-destructive, expensive and subject to radiation hazards and other limitations.

Others methods of soil moisture measurement include tensiometers, moisture blocks, gamma-ray transmission, neutron transmission, heat conductivity measurements, and Time-Domain Reflectometry (TDR) measurements. Some of these methods can be used to perform quick, non-destructive "water audits" of highway landscape sites.

The irrometer is a moisture sensor based on the tensiometer principle. In essence, the irrometer consists of a sealed water-sealed tube with a ceramic tip at the bottom . The tube is placed in the ground at the appropriate root zone depth. The porous tip allows water to be drawn out by dry soil and drawn in by wet soil. The partial vacuum created as the water volume changes is correlated to moisture levels. The sensor output provided in remote measuring applications is an analog voltage signal proportional to the internal vacuum pressure of the tube. The irrometer requires occasional maintenance and must be removed when freezing occurs.

Moisture sensors used in RIC systems use the fact that the electrical properties of some materials can be correlated to moisture levels [57, p. 59]. Resistance, capacitance and dielectric strength measurements have been used for this purpose. Earlier sensors of this type relied on resistance measurements. The current trend is toward capacitive type measurements because they are less susceptible to the presence of fertilizers and other chemicals.

In a typical RIC application, the moisture sensor is permanently placed at the root zone. To set up operation the soil is first brought to the desired moisture level. The electrical signal provided by the sensor at this time is used as a threshold ("wet") point to decide whether to irrigate or not. Because the price of these moisture sensors is still in the $200.00 range, it is a common practice to share sensors among plants having similar water requirements and soil characteristics. In other words, several stations are programmed with the same sensor. When stations in a group water sequentially, the RSC adjusts all run times in the group proportionately to that of a designated master station (usually the first one in the group to water). Some RIC systems use sensor based programming to formulate customized responses to "wet" point events reported by moisture sensors.

Moisture sensing for irrigation in general is susceptible to errors due to non-uniform water storage in the soil. In other words, limited sampling (due to cost) of the soil moisture content function can result in errors in meeting actual plant requirements. For highway landscape applications, the variety of water requirements and terrain also makes it difficult to place moisture sensors at representative points to be shared by groups of RSC stations. Very meticulous studies on the use of moisture sensing for highway landscape irrigation have been conducted by the Caltrans Transportation Laboratory [52] [53].

3.2.3 Water Recycling

Highway landscape irrigation is a natural candidate for use of reclaimed water; a method of water conservation quickly becoming established in several states. In fact, current Caltrans water conservation guidelines specify that recycled wastewater must be used for irrigation whenever available, consistent with quality and health standards and within justifiable

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cost. Water reuse for landscape irrigation involves some requirements that can be addressed readily by current RIC systems. Incidentally, SCADA systems have been used in some wastewater treatment systems [60]. Special arrangements with treatment plants are necessary to use reclaimed water [62, p. 11].

Primary and secondary treatment refer to the process of filtration and aeration normally applied to wastewater to breakdown the organic and soluble wastes before discharge into nearby bodies of water [58, p.147]. The direct reuse of water collected as waste requires application-specific levels of post-secondary treatment subject to state and local regulations [61]. For irrigation purposes the treated effluents must have not only the right sanitary quality but also the nutrient content and chemical balance necessary to meet the needs of the target soil and vegetation. For example, nitrate, potassium, phosphorous and salinity levels are of special concern in irrigation. Levels of filtration must also provide clog-free operation of irrigation equipment (this is of special concern in drip irrigation). Sometimes extra filtration must be provided on site. Health code regulations at the state and local level define the proper use of recycled water for irrigation to avoid public health risks.

The control and supervisory functions of a RIC system have many potential applications in the process of incorporating water recycling in highway landscape irrigation. Some of them relate to water conveyance issues. In cases where dual water supplies must be operated, the RIC system can easily automate the task of switching supplies. Instrumentation to monitor water quality can be installed to comply with local health code regulations. Extra filtration equipment can be operated automatically to avoid clogging of emitters or sprinklers. In cases were reclaimed water sources have limitations in flow, total volume, or availability time, RIC systems can ease the task of constraining irrigation accordingly. In some instances, climatic conditions (high winds, for example), or hydraulic system leaks might make it necessary to suspend irrigation to avoid exposing the public to treated effluents. This can be easily supported by RIC systems and is of particular importance given reported cases of lawsuits being filed when such exposures have taken place. Even though the effluents do not pose a health hazard, erroneous public perception can create bad publicity. Finally, the reporting capabilities of RIC systems, water use notably, provide documentation of compliance with the particular terms of the agreement used to obtain the reclaimed water.

3.3 RIC System Surveys

This section introduces the surveys of existing RIC systems. The purpose of the surveys is to present Caltrans landscape irrigation professionals with a quick and concise overview of the styles of irrigation management supported by state-of-the-art RIC systems.

The surveys start with an introductory statement of the system's primary target applications and supported irrigation management features. The General System Overview presents the Main Control Unit (MCU) platform, the Communication Links (CLs) supported, possible topologies, weather station support, and a brief description of the Remote Site Controller (RSC) features including data acquisition capabilities. The MCU Software section describes how the MCU software supports irrigation management. Any limitations imposed by a particular system design and design features that could be especially useful are interspersed with this description. A subjective appraisal of the software organization and user interface is also provided. Whenever available, upcoming system revisions or improvements are indicated.

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A total of fourteen system surveys is included in this section. Thompson's Mark-1 is intended for golf applications only. Although it could not be used "as is" to meet Caltrans RIC requirements, studying its features and styles may be educational and informative, perhaps providing good ideas to incorporate in a custom RIC design. For the same reason this section also presents a system that is not centrally controllable (Aquametrics' COM 1). Toro's Network 8000 and Solar Wind's System 390-B are marketed primarily as golf course systems, but they could be useful for some Caltrans applications. The rest of the systems surveyed (Buckner's COPS Universal, Griswold's IDC Central, Motorola's MIR 5000, Network Services Control, Rain Bird's Maxicom, Thompson's Mini-Mark, Valcon's V-III, and Valcon's VIP) are for general purpose use. Buckner's COPS Genesis and Rain Master's Evolution were in beta testing at the time of this report and are included to give a preview of the newest RIC systems to be available this year.

These RIC systems implement a variety of irrigation management philosophies, from the minimalist to the most full-featured. The intent of this information is to enable Caltrans landscape irrigation professionals to find the right tool to match their own styles and needs. Once the choices are narrowed down, the next suggested step is to consult the system benchmarks for an in-depth look at the systems.

3.3.1 Buckner's COPS Universal

Buckner Inc.'s Computer Oriented Programming System (COPS) Universal is designed for irrigation management in highway, municipality, park systems and golf course applications. It features time based irrigation programming, water budgeting, radio communications, and manual operation with a hand held radio unit. COPS Universal controllers are designed to retrofit any existing irrigation controllers and also can be used by themselves.

General System Overview

The Main Control Unit (MCU) is implemented on a dedicated IBM PC AT (or compatible) running DOS 2.1 or higher and equipped with: 640 Kilobytes of RAM, VGA monitor, a 20 Megabyte hard drive, one floppy drive, and an optional printer. A serial port is required to connect the external interface to communicate with the Remote Site Controllers (RSCs). In this system the RSCs are called field controllers and have very little intelligence. The MCU carries out the execution of the irrigation program, issuing all commands to the RSCs as needed. This design places a heavy burden on the Communications Link and compromises the reliability of the system in case the link fails.

COPS Universal supports radio communication only. The MCU radio interface allows direct communication with RSCs located up to 3 miles away. Both conventional radio and trunked radio links are supported but it is not possible to control mixed systems simultaneously. A maximum number of 999 RSCs and 1500 stations can be controlled by the system.

The system is designed to retrofit any existing irrigation controllers, whether they are stand-alone or centrally controlled. This is done by connecting the controller's station output terminals to a remote interface communicating with the MCU; this combination constitutes an RSC as defined in our model. The remote interface also can be provided with its own stations and housed in a Buckner enclosure. It does not provide a user interface. The RSCs may be

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operated manually with a hand held radio unit and shutdown automatically in case of communication failure with the MCU.

Field controllers are identified by a three digit unit number. Stations for a given controller are identified by a two digit valve number. Both the unit number and the valve number are needed to fully specify a station in the system.

A data acquisition board is currently under development. It will support one pulse (rate) input and two change-of-state inputs per RSC.

MCU Software

The COPS software interface is menu driven, makes use of function keys for input, and offers on-line help. However, it does not provide support for mouse and graphics.

Irrigation is managed by means of "programs." A COPS program defines time based irrigation schedules for a set of stations. Programs are identified by a two digit number and can be given descriptive names.

During operation of COPS, the view of the system is limited to the valves specified in the current program. The MCU executes the irrigation program locally and is limited to executing a single program at a time.

The main functions provided by the software are system programming, system operation, system monitoring, system configuration, and utilities. The functional groups correspond to the items in the main menu.

The system programming functions allow the user to create, edit and copy programs. Each program entry specifies up to three start and run times for a station and the way to schedule them in a seven day cycle. A Master/Slave configuration can be specified so that irrigation occurs in sequence starting with the Master station. Soon to be available is Hydro Graph, a feature that will enable users to preview the theoretical flow associated with their programs in graphical form.

The system operation functions provide flexible ways of operating the system. In auto mode, the current program is executed. In semi-auto, syringe and manual modes a set of stations is selected from the program for operation. In semi-auto mode one of the three run times for the set is executed, while in syringe mode the run time is specified by the user. Manual mode has a preset run time of thirty minutes. This function group also enables the user to shut off all the valves in the system and to suspend irrigation for up to 99 days.

The system monitoring functions allow the user to monitor the status (on or off) of valves in selected parts of the system. Multiple valves can be selected from the entire system or from a given controller. It is also possible to specify a single valve to be monitored.

Water budgeting is supported by utility functions.

COPS Universal is useful for operating irrigation systems based on timing specifications calculated and supplied by the user. There is no integrated support for ET driven adjustments or volume based programming. More importantly, the concentration of intelligence at the MCU limits the ability to control large systems reliably.

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3.3.2 Griswold's IDC Central

Griswold's IDC Central system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based irrigation programming, water budgeting, data acquisition and monitoring, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, password protection, and foreign language support.

General System Overview

The Main Control Unit (MCU) is implemented on a dedicated IBM PC AT (or compatible) running DOS 2.0 or higher and equipped with: 512 Kilobytes of RAM, EGA monitor, a 10 Megabyte hard drive, one floppy drive and an optional printer. At least one 2400 Baud Compudine modem is required for communicating with the IDC controllers (this system's Remote Site Controllers). There is no support for weather stations in the system.

IDC controllers can communicate with the MCU via conventional radio, dial telephone, cellular telephone or hard wire. The same modem can be used for both conventional radio and hard wire communication, but a separate modem is required for telephone communication. A Radio Terminal Unit is required to interface the modem to the MCU radio unit. All communications take place at 300 Baud. The system is capable of supporting a maximum of 9993 RSCs.

The RSCs can be connected in a semi-bus topology where trees are allowed (i.e., branching off to more than one controller). These type of buses can be linked to the MCU via conventional radio or telephone. Typically, up to 65 RSCs can be connected by a two mile long cable before a repeater is needed.

The RSCs are capable of stand alone operation and can be programmed locally. Stations are added to RSCs by installing plug-in output modules, in this manner, 8, 16, 24, 32, 40 and 48 station configurations are possible. Eight sensor inputs are provided, each being independently configurable as analog, digital, or pulse (rate).

The RSC's user interface features an LCD display and a keypad. Operation is menu driven, with built-in support for Spanish.

MCU Software

The IDC Central software interface is menu driven and does not provide support for mouse or graphics. The software refers to RSCs as satellites.

Irrigation is programmed on a station by station basis. A station program includes both a primary run time and an alternate run time. A combined total of up to eight start times can be specified. Start times are not allowed to overlap. The irrigation cycle has a length variable from one to 31 days; any seven days in the cycle may be designated as watering days. The current day in the irrigation cycle needs to be specified and specific days of the week can be omitted from the cycle. A station program can be copied to other stations and downloaded to

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the field. Generally, only one station per RSC is allowed to irrigate but an option is available to allow up to four stations to operate simultaneously.

Manual operations allow the user to address a controller to: start a primary program; run station primary run times in an arbitrary sequence; run a set of stations for a specified time; run its master valve for a specified time; perform an upload or download; and specify the controller's access code.

A system wide status poll can be scheduled on a daily basis or initiated manually.

The All Call feature can be used to perform shutdowns, restarts, and water budget factor changes manually for all RSCs linked via conventional radio or hard wire.

Satellite water budget factor adjustments are possible. Individual stations can be optionally excluded from budget factor adjustments.

Printed reports include an alarm summary, a field program change summary, current water budget factor values, an All Call command confirmation, and historical water use data. Reported alarm conditions include communication failures, station open and short circuits, and high and low flows.

Griswold's IDC Central provides a good environment for simple time based irrigation programming but lacks more sophisticated features such as group programming, more complete data acquisition, and feedback driven irrigation adjustments. Upcoming versions of the system will support increased program capacity, flow management, weather stations, soil model based adjustments, moisture sensing, improved reporting, and ET driven adjustments.

3.3.3 Motorola's MIR 5000

Motorola's MIR 5000 system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, volume based programming, sensor based programming, filter and fertilizer programming, water budgeting, ET driven irrigation, data acquisition and monitoring, integrated weather station support, alarm response definition, alarm paging, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, multitasking, extensive reporting capabilities, password protection, and foreign language support.

General System Overview

The Main Control Unit (MCU) is implemented on a non-dedicated IBM PS/2 model 55SX running IBM DOS 3.3 and equipped with: 4 Megabytes of RAM, VGA monitor, one floppy drive, a 30 Megabyte hard drive, an IBM Proprinter, at least one serial port, and a Motorola CODEX modem. Multitasking software is provided to allow simultaneous use of multiple programs.

A single Field Interface Unit (FIU) attaches to the MCU to support radio, hard wire and private line telephone communication with the Remote Site Controllers (RSCs). In this system, the RSCs are called Field Units. The FIU provides one port for radio communication and one for line communication.

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Radio communication is available in trunked radio, 800 Mhz conventional radio, and VHF/UHF radio versions.

Trunked radio encompasses support for the SMARTNET Trunking system and Motorola's MAXTRAC trunked radio system.

Hard wire communication uses #14-2 UF wire to connect Field Units in a bus topology for a range of up to 6 miles from the MCU.

Telephone communication requires a dedicated private line circuit.

Hard wire and telephone communication from the MCU can be mixed with conventional radio but not with trunked radio.

Up to five Field Units can be linked by hard wire to a Field Unit communicating via radio with the MCU. This is called shared radio. The total distance of cable cannot exceed 3 miles.

Three types of Field Units are supported.

The MIR5000F-MW can control up to 52 24-VAC outputs and up to 28 sensor inputs. The software can control up to eight mainlines each with a flow meter input.

The MIR5000F-SC can control up to 63 Remote Terminal Units (RTUs). An RTU consists of one DC relay or magna-latch (hydraulic) solenoid and two optional sensors. One of the sensors measures pulse rate and the other one detects change of state. The RTUs are connected to the controller using #14-2 UF cable in a bus topology extending up to 6 miles.

The MIR5000F-DC can control up to 32 DC magna-latch devices (solenoids or relays) and up to four mainlines. Up to 16 sensors can be monitored.

The Field Units are capable of initiating communications with the MCU to report alarms. They can be programmed locally for stand alone operation with a user interface similar to that of the MCU software. On line help is provided. Hebrew and Italian versions are available.

The MIR 5000 system can control up to 8000 Field Units and six weather stations.

MCU Software

The MCU software is menu driven and provides multitasking, remote terminal access from another computer (with additional software), and remote DTMF access. The system can be password protected to avoid unauthorized modification of irrigation programs.

Sets of Field Units can be grouped logically in areas that provide the top level view of the system during status monitoring. This view is presented graphically, allowing the user to "point and click" to units in an alarm condition, make water factor adjustments and enable or disable irrigation. The user is notified when new alarms are received even when not monitoring status.

The Field Units require field and main line definitions before they can execute programs.

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The field definition indicates how many and which stations are controlled by each main line. Some of these stations may be assigned to operate master valves, fertilizer pumps, and filter valves.

The main line definition includes the irrigation basis (time or volume), watering factor, filter programming data, and fertilizer programming data. The volumetric line definition includes the flowmeter rate (gallons per sensor pulse), the allowed high and low flows, the pipe fill-up time, and the leak detection setting. A leak is reported if flow is measured when irrigation is not scheduled. If the line flow exceeds the given range twice a burst alarm is reported. In both cases program execution is halted automatically by the controller. Line definitions can be given symbolic names and downloaded to specified Field Units.

Filter programming involves specifying the stations actuating the filter pumps, the duration of flushing and the interval (in time or quantity) between flushes. Fertilizer application can be programmed as a fixed quantity or proportional to the amount of irrigation water applied.

Each controller can have up to 60 irrigation programs. A program specifies the following items:

1) Watering stations: a list of which stations to actuate.
2) Watering amount specified in either time or volume.
3) Start time for program execution.
4) Stop time: At this time irrigation is stopped regardless of whether it is done or not.
5) Start condition: program execution begins when this becomes true.
6) Wait condition: program execution is delayed while this condition is true.
7) Stop condition: program execution is halted immediately when this becomes true.
8) Number of days between irrigation: from one to 60.
9) Irrigation days.
10) Number of cycles per day: the number of times the program is executed per day.
11) Interval between cycles.

Water factors can be specified at both the system and area level. The water factor for a Field Unit is the product of both the system and area water factors. Weather station support is optional and provides for automatic ET driven adjustment of system or area water factors.

Closed loop response is implemented with the specification of "if-then" rules for each program.

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The "if" condition can be a logical combination of a time test, a pulse rate sensor value test, a sensor change of state, or a station open/close test. Pulse rate sensor values can be scaled by a user defined equation.

The resulting action can be to change the water factor, start/stop a mainline, open/close a station or flag an external condition. The actions can be applied to any station, area or the entire system.

Programs can be uploaded, copied, edited, renamed, deleted, undeleted and printed.

The MCU allows the operator to set priorities for reported events and to view them selectively. Types of events include MCU restart, communication with Field Units, alarms from Field Units and remote access of the system. The system can be instructed to page a specified operator when a given event is received. The events can be annotated by the operator to record the action taken.

The MCU can be instructed to poll selected Field Units periodically to gather system data. The type of data and the time window and frequency of polling are specified in interrogation schedules, which are then assigned to Field Units. The accumulation management feature enables reporting of water and fertilizer consumption for user defined areas.

The SETCALL feature enables the user to address selected Field Units simultaneously, for example, to adjust the water budget factor.

An automatic dispatcher provides schedulable unattended execution of program downloading and system adjustments.

Manual operation of Field Units is supported. During manual operation more specific status information can be monitored.

Overall, the user interface is very good. The user is provided with complete help on most screens. Choice lists are used to minimize memorization requirements. The main menu organizes logically the functions of the system in three areas: irrigation programs, management programs and system definitions. In terms of irrigation features, infiltration rate adjustments and soil model based adjustments are not supported. A recent software revision incorporates infiltration rate compensation.

3.3.4 Rain Bird's Maxicom and Maxicom Jr.

Rain Bird's Maxicom system is designed for highway, municipality, and park systems applications. It features time based programming, sensor based programming, water budgeting, ET driven irrigation, flow optimization, soil model based adjustments, infiltration rate compensation, data acquisition and monitoring, integrated weather station support, alarm response definition, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, extensive reporting capabilities, password protection, and foreign language support. Maxicom Jr. is a single site version of Maxicom.

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General System Overview

The Main Control Unit (MCU) is implemented on a non-dedicated IBM PS/2 model 50 (or compatible) equipped with: 640 Kilobytes of RAM, VGA monitor, one floppy drive, a 20 Megabyte hard drive, an EPSON dot-matrix printer, a serial port, and a modem.

Dial telephone, cellular telephone, conventional radio, trunked radio, and hard wire communication interfaces are available.

The conventional radio interface has a typical 20 mile range before repeaters are needed, actual ranges depend on terrain. It consists of a 450-470 Mhz UHF-FM transceiver/modem, a power supply, and an antenna.

The trunked radio interface consists of a radio transceiver, a modem, a power supply and an antenna.

Both dial and cellular telephone communications require a Hayes compatible modem to be connected to the MCU. For cellular telephone, the remote site communications interface requires a cellular data interface, a cellular telephone, and a power supply.

A Remote Site Controller (RSC) consists of a Cluster Control Unit (CCU) and a mix of up to 28 Satellite Units and decoders. The satellites and decoders are hard wired to the CCU in daisy-chain fashion by a two-wire flat pair. Alternatively, the satellites can be connected to the CCU using existing telephone twisted pair cable and a terminal block at the CCU. In the generic RIC model, a CCU is equivalent to an FCU; and the combination of Satellite Units and decoders is equivalent to an FSCU. It is assumed, although not necessary, that a site is controlled by a single CCU.

The Satellite Units perform the actual irrigation. Two types of controllers are available: ISC-SAT and SBM-SAT. The first type is solid state and features a keypad for manual operation. The latter simulates an electromechanical device and uses dials for manual operation. ISC-SAT units can control 12 or 24 stations, while SBM-SAT units control 12 stations. Both of them switch to standby mode when communication with the CCU fails and return to normal mode when communication is resumed. In standby mode, the satellite units execute the instructions that have been programmed locally. Instructions specified by the MCU are stored in the CCU and cannot be altered from the field.

Pulse, output and sensor decoders are available. A pulse decoder senses pulse rate information. An output decoder actuates a dry switch contact. A sensor decoder reads the state of a switch.

Up to eight weather stations can be connected to the system by hard wire, dial telephone, cellular telephone, or private line telephone interfaces. Weather station data can be monitored in real time and their statistics can be displayed in graphical form.

The maximum number of CCUs controlled by Maxicom is 200, whereas Maxicom Jr. is limited to a single CCU.

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MCU Software

The Maxicom software is menu driven and features on-line help assisted programming. Mouse support is not provided and graphics are limited to graph displays.

The site definition option is used to specify the CCUs on the system, how they are to be contacted, which weather station they are assigned to, the value of their water budget percent multiplier, the times for schedule transmission and data logging, and the baud rate to be used. Uploads and downloads occur only once per day and the CCUs are not capable of initiating communication, which somewhat limits the timeliness of alarm reports.

The ET Schedule Planner option uses a rain bucket model to describe a weather station site. This model pictures the plant root zone as a water reservoir of fixed capacity having inputs and outputs. The inputs are rainfall and irrigation water, while the outputs are evapotranspiration losses and runoff. Runoff occurs when the maximum infiltration rate and/or the capacity of the reservoir are exceeded.

The user defines the fixed rain bucket parameters for each weather station in the system. When a schedule executes, the rainfall and reference ET data gathered by its weather station are used to calculate the daily water demand and total station run times. The reference ET is adjusted for each station as specified by the user to account for different vegetation, plant growth, terrain features, and other factors. A convenient feature is the ability to see how different ET values affect station run times.

Station run times are adjusted by water budgeting or directly when weather stations are not available.

A Maxicom schedule is a specification of how a CCU is to perform irrigation expressed in a custom programming language. There are two types of instructions: control instructions and step instructions. The former are used to specify when the schedule is to be executed, how its execution is affected by sensor inputs and how flow monitoring is to be performed. The latter are used to specify station run times, decoder operations, timed pauses, loops and schedule linking. Schedules can include comment lines for documentation. Programming is aided by multiple levels of on-line help so that the user need not memorize the syntax of the language. Up to 100 schedules can be defined for a CCU. There is no way to assign the same schedule to multiple sites without retyping it under a different name.

Schedule execution can start at a preset time on specified days of the week or on a user specified cycle with a period of up to 99 days. It also can be triggered by a specified sensor reading or by another executing schedule. Sensor inputs also can be used to cancel and advance schedule execution. They also can be used to start, cancel, interrupt, un-interrupt and advance other schedules. A schedule can be repeated up to nine times in a day or it can be repeated continuously. A time window can be defined to restrict when irrigation takes place.

Station run times can be defined flexibly for arbitrary satellite station groups. Cycle and soak is a feature that allows the system to break up the total station run time in cycles in order to avoid runoff. The user needs to specify the maximum "on" time per cycle and the minimum soak ("off") time between cycles. Once the schedule is specified, the user may simulate a "dry run" to verify the correctness of the schedule before it is actually executed. The "dry run" provides a plot of projected site flow vs. time.

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Maxicom also has the ability to monitor and log site flow information. This information can be used to detect and react to malfunctions in the hydraulic system. The system can be instructed to isolate the fault automatically and to stop irrigation in the faulty zone. Or it can be instructed to execute a set of user instructions to deal with the situation. When flow management is used, the system is capable of modifying the execution of a schedule to optimize water flow.

Certain system parameters such as water budget factors and precipitation rates can be defined in tables and referred to by name. This feature facilitates schedule updating and management.

Feedback data from sites and weather stations can be monitored in real time or logged on a long term basis. Viewing these data, the user can determine the current status of a station, its accumulated run time, times when malfunctions occurred, etc.

Maxicom provides a powerful environment for time based irrigation control. The system features reveal the manufacturer's willingness to incorporate suggestions from practicing landscape irrigators. Some improvements could be made to the user interface. For example, the user is required to identify schedules by site and number without a choice list; this could be cumbersome for large systems. Several prompt sequences are too long and should be replaced with dialog boxes. Also, on-line help should be provided for every screen of the program.

The arrangement of functionality could be better organized as well. For example, once a schedule is selected, the user should be able to view, edit, simulate, print or download it from the same screen. An upcoming version of the Maxicom software will feature an improved user interface and a tutorial program to help users learn the system.

Introduced January 1, 1992, the Mirage and Turfmaster controllers feature increased station capacity and improved user interfaces. The Turfmaster controller is microprocessor based but uses dials and LEDs as a user interface. Available in 12, 18 and 24 station configurations, the Turfmaster can store up to three irrigation programs capable of running sequentially or concurrently. In addition to supporting water budgeting, variable irrigation cycles, cycle and soak, and variable rain shutdown, this controller also supports two sensor inputs.

The Mirage user interface features an LCD display and individual buttons for most functions. Available in 12, 16, 24, 36 and 48 station configurations, the Mirage can store up to four irrigation programs capable of running sequentially or concurrently. Independent station control is also provided. In addition to supporting water budgeting variable irrigation cycles, independent station cycle and soak, variable rain shutdown and password protection, the Mirage also supports up to four sensor inputs.

3.3.5 Thompson's Mini Mark

Thompson's Mini-Mark system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It is a general purpose version of Thompson's Mark-1; the field hardware for both is the same. It features time based programming, water budgeting, ET driven irrigation, flow optimization, moisture sensing, data acquisition and monitoring, integrated weather station support, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed

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intelligence, multitasking, a graphical user interface, extensive reporting capabilities, data export support, and foreign language support.

General System Overview

The Main Control Unit is implemented on an Apple Macintosh Classic running Macintosh System 7 and equipped with: a 40 Megabyte Hard disk, 2 Megabytes of RAM, a Communications Interface Adapter, and an Imagewriter II printer. The Mini-Mark software requires Hypercard 2.0 to run.

The Remote Site Controllers are called satellites. Up to 100 of them can communicate bidirectionally with the Main Control Unit via hard wire, dial telephone, cellular telephone, and conventional radio. The system supports one weather station that requires a separate Communication Link (conventional radio, dial telephone, cellular telephone, or hard wire).

Hard wire communication requires a 16 AWG stranded twisted pair. The satellites connect in a semi-bus topology where trees are allowed (i.e., branching off to more than one satellite). Optional repeaters are used to extend the maximum path distance of 5000 feet. Each segment between repeaters can support a maximum of 20 satellites, and a maximum of 20 segments is allowed in the system.

The satellite controllers come in 12, 18, 24, 30 or 36 station configurations. They execute the irrigation programs locally and can be operated via TRC hand held radio units.

Mini-Mark irrigation controllers can be equipped with up to six sensors: one pulse sensor (flow only), and five digital sensors (one rain switch and four soil moisture sensors). Moisture sensors have an adjustable "wet" point. A program for which a moisture sensor has been installed will stop irrigation when its "wet" point is reached.

The controller's front panel features an LCD display and a membrane keypad. Separate keys are provided for each station and function. Spanish, Japanese and French user interfaces are available.

MCU Software

The Main Control Unit software features a point and click graphical user interface. The different areas of the program are represented by icons on which the user clicks to access. No typing is required or allowed, all data are entered by clicking on icons.

The Navigation screen provides a central point of access for all the areas of the software. It displays icons for the irrigation groups, satellites, reports, communications, transmission logs, preference settings, syringe schedules, rain switch status, flow data, weather data, and home (initial screen). This screen is directly accessible from most screens in the program.

Each satellite controller offers four programs named A, B, C, and D. The first three run sequentially, i.e., they don't overlap. Program D is allowed to overlap with the other programs and is intended for drip irrigation. Each station assigned to a program is given a run time and a number of repeats. Stations assigned to a program run in numerical order. A

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program can have up to 12 start times and can be specified to run on specified days of the week. Also associated with each program is a water budget percent multiplier.

The Groups screen is used to define the system's control method, program water budget factors, and to define scheduling parameters for up to 20 satellite groups. The control method refers to how irrigation is adjusted: Auto ET, Manual ET, and Manual Time (global percent). A system wide water budget factor can be assigned to each of the four (A-D) programs. Each group of satellites can be given up to 12 start times and a set of days of operation in a weekly cycle for each program.

The Satellite screen is where satellites are assigned to groups and their locations are defined. This is also where satellite stations are assigned programs, run times, number of repeats and are included in syringe schedules.

The Communications screen is used for uploading and downloading operations for the entire system or specified satellites. Program data can be uploaded from the field and can be compared to the data specified at the MCU to identify changes made at the field. MCU program data can then be updated from the uploaded data. The time for program download can be set. From this screen any or all satellites can be turned off or set to AUTO mode.

The Syringe screen allows the user to schedule or manually operate syringing for satellite groups. The order of execution of stations in any satellite can be previewed.

The Weather screen displays complete evapotranspiration data with average, minima and maxima values.

The Flow screen displays flow data for satellites equipped with flow sensors.

Mini-Mark aims to offer a very user friendly interface for computer controlled irrigation. The lack of run time adjustment capability within a group limits its usability in large scale applications. Some room for improvement exists for its data acquisition and alarm reporting features.

3.3.6 Toro's Network 8000

Toro's Network 8000 system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, water budgeting, ET driven irrigation, flow optimization, soil model based adjustments, infiltration rate compensation, extensive environmental adjustment factors, data acquisition and monitoring, integrated weather station support, alarm response definition, a variety of communication interfaces, radio communications, distributed intelligence, a graphical user interface, extensive reporting capabilities, and foreign language support.

General System Overview

The Main Control Unit (MCU) is implemented on a dedicated AT class IBM compatible running DOS 3.3 and equipped with: four Megabytes of RAM, VGA monitor, math co-processor, 120 Megabyte hard drive, one low density 3.5" floppy drive, a mouse, and an IBM Proprinter. A serial network controller PCB provides two communication paths to communicate with the Remote Site Controllers (RSCs); in this system the RSCs are called

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satellites. The system is capable of supporting up to eight communication paths by adding additional serial network controller PCBs. Each communication path can support a maximum of 100 satellites.

Satellites are connected in daisy-chain fashion using a 16 gauge communication wire pair looping back to a surge protection unit. The loopback is recommended but not required. This satellite loop can then be directly connected to the MCU or connected using telephone lines or conventional radio communications. The total length of the wire loop has to be less than 5 miles.

Conventional radio communication uses a Motorola RNeT telemetry modem and has an approximate maximum range of 3 miles extensible by means of repeaters.

Satellites are grouped in Central Satellite Groups (CSGs). Up to 16 CSGs can be present in a system. Both a CSG address and a satellite address are necessary to identify a particular satellite.

Satellites are capable of stand-alone operation and can be programmed locally. Each satellite can control a master valve or pump start and up to 32 stations, and can store up to 12 irrigation programs. Satellites can be equipped with up to eight sensors: one for temperature, one for pressure, and six pulse (rate) or change of state inputs.

A Monitor Control Unit is available to expand the input/output capabilities of the system. This unit is linked to the central computer in the same fashion as the satellites. It provides 12 pulse rate inputs, two analog inputs (pressure and temperature), and eight 24-VAC station relay outputs (for pump control, etc.).

MCU Software

The Network 8000 provides a very advanced graphical, point-and-click user interface.

A description of a microenvironment to be irrigated is called a watering plan. It is composed of adjustment factors to account for water pH factor, type of sprinkler nozzle, head pressure, sprinkler spacing, watering arc, plant type, soil type, terrain type and user preference. The system is capable of storing up to 999 watering plans.

In this system an irrigation program consists of a specification of the number of starts per week, repeats, active days and location groups. The actual run times are calculated by the system to satisfy demand ET considering the soil capacity, soil infiltration rate, and measured rainfall. The user can preview the calculated run times and override them if necessary. ET data can be obtained from a variety of sources such as weather station data, historical ET data, CIMIS, satellite temperature data, etc. The system is capable of supporting one weather station only.

The number of repeats (zero to three) is used to determine the number of applications used to supply the demand ET, with zero repeats resulting in a single application and so on. A soak time between repeats of zero to 99 minutes can be specified. Irrigation is restricted to a user specified system wide time window. Programs are identified by number and are also given descriptive names. Up to 16 unique programs can be assigned to a CSG.

Each program is associated with a (possibly sub-divided) location group. A location group indicates which sub-areas of the site are irrigated by the program, e.g., holes in the case

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of a golf course. Programs are then assigned to stations by location codes. The location code is made up by concatenating the sub-area number and the first letter in the program name. A station may be assigned to more than one program.

Start times are assigned per CSG. Each satellite can be configured to delay execution of programs by a given offset in minutes (start skew). Also, a satellite can be assigned to a sequence group indicating the order in which programs are to be executed. Start skews, sequence groups and the ability to set the maximum number of simultaneously executing programs in a satellite can be used to smooth out flows in the system. The maximum number of programs that can run concurrently can be set from one to six. The software provides assistance in the calculation of the necessary parameter values. Programs are queued by start time and then by program number when the maximum number of simultaneously executing programs is exceeded.

Utility time based programming is supported by syringe programs and sequential multimanual programs. The former allow a single run time to be specified for a designated station. The latter permit up to 32 sets of selected stations on a designated satellite to run for one to 30 minutes in a designated sequence on specified days.

Alarm thresholds can be defined for temperature, pressure, flow and wind speed sensors. A set of user selected responses is activated when a threshold is violated for a specified period (called a qualification time). There are seven possible response actions: send a timed pause instruction to a designated satellite(s), send a pause-off (resume) instruction to a designated satellite(s), turn a switch on for a specified period, turn a switch off for a specified period, send a cancel instruction to a designated satellite(s), send a rain hold instruction to a designated satellite(s), and send a rain hold and cancel instruction to a designated satellite(s).

An alarm threshold can be set for satellite triac current but no response action can be specified. The alarm may be disabled.

Control codes can be manually sent to the MCU from a satellite control panel. Upon receiving this code the MCU can cancel or rain hold the source CSG or all the CSGs, start any one of eight sequential multimanual programs, or cause a down-load to satellite (this recalculates all run times).

Manual operation allows immediate program downloading to designated satellite(s) and starting, cancelling, and holding program execution. Also, messages can be sent for display at designated satellite(s) control panel(s).

Reports provided by the system include satellite program data, projected flow, actual flow, field program changes, field errors, digital input monitoring and flow monitoring. Field sensor data are collected hourly and logged on the hard disk. They are displayed in graphical form.

The Network 8000 system supports both English and French user interfaces.

Network 8000 provides a powerful environment for time base programming with ET driven adjustments. The use of cryptic codes for plan adjustment factors, location codes, and alarm responses is cumbersome. Help and status screens are available from most screens.

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3.3.7 Aquametrics' Com-1

The Aquametrics' Com-1 controller is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, infiltration rate compensation, moisture sensing, and data acquisition and monitoring. Although it can be centrally monitored, it cannot be centrally controlled.

General System Overview

The Com-1 controller is available in 16, 24, 32, 40, and 48 station models. Its front panel provides a column of three keys for each station to be controlled, an LCD display, and six additional keys for selecting features and programming. Operation is not menu driven and requires memorization of non-intuitive key press combinations.

A serial port is provided for field adjustments and data acquisition with a portable computer. A remote link via dial telephone, cellular phone, or radio is also possible for these purposes.

The controller is capable of storing two irrigation programs. An irrigation program consists of a time window of operation; dwell, soak and maximum watering times for each station in the program; and days of operation. The time windows for the programs must not overlap and must be separated by at least one minute. The days of operation can be set in a fixed irrigation cycle of two weeks. The dwell times specify nominal run times, while the soak times specify the minimum time a station will remain inactive after watering. Normally, the active stations assigned to a program run sequentially in station number order for a period equal to their respective dwell times. Each one of these passes is called a scan. A station remains inactive for the rest of the day when its total run time becomes equal to or greater than its maximum watering time.

Moisture sensor units can be added to provide feedback to the irrigation programs. A moisture sensor unit is usually connected to a master station and shared with a group of selected slave stations. This master/slave assignment requires the use of a computer. The sensor's "wet point" must be manually adjusted. Irrigation takes place as programmed only when the sensor reads below the "wet point." The sensor adjustment unit itself inhibits irrigation when the threshold is reached by opening the valve circuit. The controller notes the run time of the master and assigns it to the slaves. Moisture sensor feedback can be suspended until the next scheduled day of operation by using the Automatic System Override option.

Scans can be manually started in any one of three ways. First, all enabled stations can be set to run for a minute with the moisture sensors disabled. Second, a program scan can be initiated with the sensors enabled. And third, a program scan can be initiated with the sensors disabled. Additionally, groups of up to four stations can be run simultaneously for their dwell times. Again, this can be done with the moisture sensors enabled or disabled.

When installed with a flow meter and a master valve, the controller can detect and report excessive flow and no-flow conditions. Threshold limits for excessive flow are assigned on a station by station basis for maximum flexibility. When excessive flow is detected during a scan, the currently active station is turned off and an excessive flow alarm is reported including the station number. If excessive flow is detected for four successive stations during a scan or when no irrigation is scheduled, an alarm is reported and the

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controller shuts down until the alarm is cleared. Open circuits and short circuits are also detected.

Reports on flow data, actual station times, and detected faults can be uploaded to a host computer.

Aquametrics' Com-1 provides a simple environment for time based irrigation programming with moisture sensor feedback. Its two major deficiencies are a cumbersome user interface and the lack of full central control.

3.3.8 Buckner's COPS Genesis

Buckner Inc.'s Computer Oriented Programming System (COPS) Genesis is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, water budgeting, integrated weather station support, and distributed intelligence.

General System Overview

The Main Control Unit (MCU) is implemented on a non-dedicated IBM PC XT/AT (or compatible) running DOS 2.1 or higher and equipped with 512 Kilobytes of RAM, CGA monitor, a 10 Megabyte hard drive, one floppy drive and an optional printer. A serial port is required to connect the external interface to communicate with the remote site controllers and weather stations. In this system the Remote Site Controllers (RSCs) are called field controllers; a total of 99 separate systems, each having 999 RSCs, can be controlled. Up to four weather stations are supported for weather data collection; no automatic ET driven adjustments are supported. COPS Genesis does not support other data acquisition or event driven programming.

Three MCU communication interfaces are planned: hard wire, radio and dial telephone. All of them implement two-way communication. Only hard wire communication was available for the review version release.

The MCU hard wire interface allows three separate communication legs. Field controllers and weather stations are connected to a communication leg in daisy-chain fashion using a single 18 gauge communication pair. Each communication leg is laid out in a bus topology. Controllers and weather stations can be up to 10,000 feet apart before repeaters are needed to regenerate the electrical signals.

Field controllers are capable of stand-alone operation and can be programmed locally. They are available in 12, 18, 24 and 36 station configurations.

Field controllers are identified by a three digit unit number. Stations for a given controller are identified by a two digit number. Field controllers execute their programs autonomously from the MCU. Their front panels are equipped with an LCD display and a keypad for local programming.

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MCU Software

The COPS software interface is menu driven and makes use of function keys for input. However, it does not provide support for mouse and graphics.

The main functions provided by the software are irrigation programming, field configuration, reports, manual operations, system parameter definition, weather data, and file utilities. The functional groups correspond to the items in the main menu.

The irrigation programming functions allow the user to create, edit and transmit/receive time based irrigation program files. There are three program types: independent, concurrent and master couple. Independent programs run in parallel, i.e., they can overlap. Concurrent programs can run concurrently but do not allow start times within a program to overlap, forcing them to sequence in order of start time. Master couple programs sequences all overlapping start times ordering them for execution by increasing start time.

Each program defines up to four start times for a controller. In addition to station run times, each start time also specifies: an end time, the days the irrigation is to take place, the number of days to skip, the number of times to repeat the application, the delay between applications, the program type, and a percent multiplier for water budgeting. Times can be specified in minutes or seconds and the irrigation cycle length can bet set from one to 32 days. A program file stores programs for up to 999 different controllers, up to five programs per controller. Program files can be downloaded to the system or uploaded from the system. RSCs are capable of storing five programs.

Field configuration allows addition and deletion of field controllers and weather stations, as well as modification and creation of system specifications. System specifications are system name, language type, communication type, hardware port ID, shutdown delay, menu blackout time and measurement data units. The version reviewed (v 0.83) only supported English, local hard wire communication and English units. Because the communication type attribute is a system attribute, all controllers in a system must use the same communication type.

The manual operations functions provide flexible ways of operating the system. A manual sequence operates up to six stations for a specified period, either sequentially or in parallel. Also a controller's program start time can be executed in sequence (semi-automatic mode). Irrigation can be stopped, or suspended for rain and then resumed.

The system reporting functions allow the user to view a system activity log, the current irrigation program in the field, any of the irrigation programs stored in disk, weather reports, and the system configuration file.

The system parameters definition functions allow the user to set the time of day, day of schedule, schedule length, and time of day change.

The weather data functions allow manual weather data entry, weather data monitoring, and weather data adjustment.

The file utilities allow listing, deleting and renaming program files.

COPS Genesis provides facilities for simple time based irrigation programming with the guiding philosophy that the user is always responsible to calculate and adjust run times.

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Users expecting assistance in the form of automated calculations will be disappointed. Alarm handling is poor.

3.3.9 Network Services Control

Network Services Control is designed for irrigation management in highway, municipality, park systems and golf course applications. Network Services Control is a subscription service to transmit water budget information to retrofitted irrigation controllers via geosynchronous satellite communications.

General System Overview

The system's Main Control Unit (MCU) receives customer requests to send water budget factors to specified controllers or groups of controllers by calling a toll-free telephone number. The user sends its request by entering its user number and command codes with a touch tone telephone. A computer voice annunciator prompts the user for the required entries and repeats the commands entered. The commands are then sent to the field controllers via a third party geosynchronous satellite data carrier.

There are three types of subscription services. The basic service sends the commands received once a day in the early evening. The Immediate Transmission service sends commands as soon as they are received. The Automatic Control service eliminates the need to have the user calculate and send its own corrections: the changes are made based on ET data as specified by the user in the service agreement.

Percentage Control Adaptors (PCAs) are used to retrofit existing irrigation controllers. The PCA is connected between existing controllers and the actual valves performing the irrigation. It can fit in an existing enclosure. A small dome antenna is used for communications. PCAs come in 12 and 24 station configurations. Each PCA has a user defined address composed of a four-digit identification number and a two-digit group number. By assigning the same address to more than one PCA more than 24 stations can be controlled. The PCA senses and remembers the base run times for the valves to which it is connected. The valve run times can be adjusted from zero to 999% in one-percent increments. The customer purchases the PCAs and then pays a communications fee to have its commands sent to the field.

Communications with the PCAs are one-way only. As a result, no supervision or data acquisition is possible. The data are transmitted twice and include a Cyclic Redundancy Check (CRC) code. The CRC code is used by the PCA to verify the integrity of the received data.

3.3.10 Rain Master's Evolution

Rain Master's Evolution system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, water budgeting, infiltration rate compensation, moisture sensing, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, multitasking, and a graphical user interface.

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General System Overview

The Main Control Unit (MCU) is implemented on a non-dedicated IBM PS2 model 70 running OS 2 and equipped with: six Megabytes of RAM, VGA monitor, a 60 Megabyte hard drive, one floppy drive and an optional printer. In this system the Remote Site Controllers (RSCs) are called satellite controllers; a total of 25245 RSCs can be controlled.

Supported Communication Links from the MCU to the remote sites include UHF radio, dial telephone, and cellular telephone. A hard wire interface board with support for four to eight communication paths is under development. When radio is used a serial port is needed to connect to the base radio unit.

At the field, RSCs are hard wired together in a daisy-chain fashion using a single communication pair. Each hard wire communication path is laid out in a bus topology and can connect up to 100 controllers. The maximum distance between controllers is 2,000 feet. Only one controller per communication path needs to be linked back to the MCU.

The RSCs are capable of stand-alone operation and can be programmed locally. They are available in 6, 12, 18, 24, 36, 42, and 48 station configurations. Two master valve/pump outputs are provided.

The RSCs execute their programs autonomously from the MCU. Their front panels are equipped with an LCD display and a keypad for local programming. A local password can be specified to protect the controller from unauthorized use.

Flow and moisture can be measured by adding sensors to the RSCs. Two flow sensor (pulse) inputs, eight moisture sensor inputs, two user defined analog inputs, and two user defined digital inputs are provided.

A remote control radio unit is available for manual operation at the field site. The controllers can be code protected to avoid unauthorized access. A wiring harness is also available to enable the remote control unit to operate third party controllers.

MCU Software

The MCU software is menu driven and provides mouse support.

The current version of the software supports satellite programming only. Satellite programming enables the user to program each satellite individually, in fact, one way this can be done is by interacting with a graphical portrayal of the controller's front panel.

Each controller can have up to 15 irrigation programs, which can be assigned their own water budget factor. A program can have up to eight start times. The user has a choice between a 14 day irrigation cycle, a 31 day irrigation cycle, or a variable irrigation cycle of one to 90 days. Specific dates can be omitted. Regular programs have run times assigned to each station; Quick Station programs allow groups of consecutive stations to be assigned a run time. A delay between stations can be specified and overlapping of station on times can be enabled and disabled.

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Irrigation can also be programmed with moisture sensors for which a trip point is set. A program is associated with each moisture sensor, with up to eight sensors supported. In this case irrigation takes place until the sensor reaches the "wet" point. When this happens all run times in the program are adjusted by the percentage of run time elapsed so far.

In yet another mode, irrigation can be programmed to take place continuously during a specified time window, with a specified soak period to avoid runoff.

With the aid of flow meters, the controllers can detect overflow and underflow conditions, mainline breaks, and unscheduled flow. A controller is capable of responding to an alarm without mediation from the MCU. The controller can be set to respond to an alarm condition by providing an alarm indication and (optionally) shutting down irrigation.

Manual operations include manual program start and stop, single and multiple valve operation, test sequencing and putting the controller on rain hold.

Future versions of the system will feature trunked radio communications, group programming, volume base irrigation programming and flow optimization. Group programming will allow arbitrary groups of controllers to be programmed with environmental factors and have their run times calculated based on ET data gathered from a weather station.

3.3.11 Solar Wind Systems' 390-B

Solar Wind Systems' 390-B, one of the first remote control irrigation systems, is primarily designed for golf course applications. It features time based programming, water budgeting, data acquisition and monitoring, a variety of communication interfaces, radio communications, and manual operation via hand held radio unit.

General System Overview

The Main Control Unit (MCU) is implemented on a custom-built STD bus computer and is called the Main Control Terminal (MCT).

Field Switching Terminals (FSTs) are used to switch valves on and off at the remote sites. They correspond to dumb Remote Site Controllers (RSCs) in our model, the MCU being responsible for performing timing functions and issuing commands as needed. FSTs are available in 16 and 24 station configurations. There are two models available, the FST-B and the CR/FST-B.

A Line Amplifier is used by the MCU to interface to a two wire bus connecting the FSTs. Conventional radio and dial telephone communications are also supported. The System 390-B is capable of supporting a maximum of 128 FSTs. The MCT resends commands to the FSTs every minute; if the FST detects a communication failure with the MCT, it shuts down the valves within 2.5 minutes.

The FSTs have user defined addresses. Valves in the system are identified by a number in the range from one to 3072, which is the maximum number of stations supported (128x24).

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The FSTs may be operated manually at the remote site from their front panel or with a hand held radio unit. The CR/FST-B model is equipped with a card reader to accept local programming instructions and is thus capable of stand-alone operation, offering similar features as when controlled by the MCT. Although microprocessor based, the FSTs use dials and switches for front panel operation.

MCU Software

The MCU software interface combines menus and command lines.

Irrigation programming is done by groups, which are user defined arbitrary sets of valves. There are three types of groups: irrigation, syringe and drip. Valves in irrigation groups water sequentially in the order specified by the user; valves in syringe groups water simultaneously for one to nine minutes, all for the same duration; and valves in drip groups water simultaneously for up to 48 hours, each valve having independent run times. Groups are identified by name and number. Group numbers one to 100 are reserved for irrigation groups, group numbers 101 to 150 are reserved for drip groups and group numbers 151 to 200 are reserved for syringe groups. Irrigation and drip groups can have up to 30 valves, while syringe groups can have up to 32 valves.

Each group may have up to four start times and their valves may have up to eight independently set repeats. Six schedules (A-F) of 14 days each can defined by the user and then assigned to valve groups. Group run times can be adjusted by a group water budget factor, a system wide adjustment is also available.

Chains of up to 20 groups each can be defined to sequence group irrigation in a specified order. Chains have no names and are identified by their lead group number, which is made possible because groups can only belong to one chain.

Commands are provided to initiate, stop, pause, and resume automatic group irrigation.

Any valve in the system can be manually opened or closed from the program. A valve state table is available to monitor the state of all the valves in the system. A valve activity table logs which valves have been commanded to turn on.

The optional Flow Monitoring and Alarm System provides graphic display of sensor readings and alarm reporting. It can be used as a stand-alone system or with the System 390-B. Support for flow meters, anemometers, rain-gauges, ET pans, thermometers, etc., is provided. A Network Communications Unit is used to gather data from sensors connected by a two wire loop. Radio telemetry is also available.

3.3.11 Thompson's Mark-1

Thompson's Mark-1 system is designed for irrigation management in golf course applications. It features time based programming, water budgeting, ET driven irrigation, flow optimization, moisture sensing, data acquisition and monitoring, integrated weather station support, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, multitasking, a graphical user interface, data export support, and foreign language support.

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General System Overview

The Main Control Unit (MCU) is implemented on an Apple Macintosh IIsi running Macintosh System 7 and equipped with a 40 Megabyte Hard disk, four Megabytes of RAM, a 13 inch Apple Color Monitor, a Communications Interface Adapter, and an Imagewriter II printer. The Mark-1 software requires Hypercard 2.0 to run.

The Remote Site Controllers (RSCs) are called satellites. Up to 400 of them can communicate bidirectionally with the Main Control Unit via hard wire, dial telephone, cellular telephone, and conventional radio. The system supports one weather station that requires a separate Communication Link (conventional radio, dial telephone, cellular telephone, or hard wire).

Hard wire communication requires a 16 AWG stranded twisted pair. The satellites connect in a semi-bus topology where trees are allowed (i.e., branching off to more than one satellite). Optional repeaters are used to extend the maximum path distance of 5000 feet. Each segment between repeaters can support a maximum of 20 satellites, and a maximum of 20 segments is allowed in the system.

The satellite controllers come in 12, 18, 24, 30 or 36 station configurations. They execute the irrigation programs locally and can be operated via TRC hand held radio units.

Mark-1 irrigation controllers can be equipped with up to six sensors: one pulse sensor (flow only), and five digital sensors (one rain switch and four soil moisture sensors). Moisture sensors have an adjustable "wet" point. A program for which a moisture sensor has been installed will stop irrigation when its "wet" point is reached.

The controller's front panel features an LCD display and a membrane keypad. Separate keys are provided for each function and station. Spanish, Japanese and French user interfaces are available.

MCU Software

The Main Control Unit software features a point and click graphical user interface. The different areas of the program are represented by icons on which the user clicks to access.

The Master Schedule screen is used to define the system's pump capacity, control method and flow optimization priority scheme. The control method refers to how irrigation is adjusted: Auto ET, Manual ET, and Manual Time (global percent). The pump capacity defines the target flow used for flow optimization. When using Auto Flow Optimization, the software rearranges station execution order automatically to keep the system flow as even as possible without exceeding the target flow. In contrast, Schedule Priority enables the user to specify the order of irrigation.

The Navigation screen provides a central point of access for all the areas of the software. It displays icons for the irrigation areas, scheduler, reports, communications, preference settings, and home (initial screen). This screen is directly accessible from most screens in the program.

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Each satellite controller offers four programs named A, B, C, and D. The first three run sequentially, i.e., they don't overlap. Program D is allowed to overlap with the other programs and is intended for drip irrigation. Each station assigned to a program is given a run time and a number of repeats (up to 15). Stations assigned to a program run in numerical order.

Irrigation areas are predefined as greens, tees, fairways, roughs and others, they cannot be named otherwise by the user. Each area can be assigned a water budget percent multiplier. The greens, tees, fairways and roughs are further subdivided by hole number, e.g., green 1, fairway 17, etc. A station data table and a (customizable) station map are provided for each of these sub-areas. The station data table has entries for the satellite number, station number, program (A-D), run time, nozzle type, pressure, GPM, number of heads, degrees, radius, precipitation rate, and syringe programming setting.

The scheduler screen allows the user to specify 10 watering schedules and six syringe schedules. The watering schedules specify up to 12 start times and the irrigation priority of the different turfs (green 1, etc.). From each watering schedule screen the user can review station start and end times. The first seven watering schedules correspond to the days of the week; the last three allow the user to set up weekly schedules. The syringe schedules define start and run times for stations enabled to syringe.

The communications screen is used for uploading and downloading operations for the entire system or specified satellites. Program data can be uploaded from the field.

The reports screen presents reports for weather data, water usage by turf type, flow history, satellite station turf and program assignments, rain switch status, and flow monitoring. Weather history data can be exported to the Microsoft Excel spreadsheet program for further analysis (Mark-1 automatically launches Excel with the appropriate data).

A Japanese version of Mark-1 is available.

Mark-1 aims to offer a very user friendly interface for golf course irrigation. Some room for improvement exists for its data acquisition and alarm reporting features.

3.3.13 Valcon's V-III

Valcon's V-III system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features time based programming, water budgeting, moisture sensing, data acquisition and monitoring, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, and password protection.

General System Overview

The Main Control Unit (MCU) is implemented on a dedicated IBM PC XT (or compatible) running DOS 2.0 or higher and equipped with 256 Kilobytes of RAM, EGA monitor, a 20 Megabyte hard drive, one floppy drive and an optional printer. In this system the Remote Site Controllers (RSCs) are called field satellites.

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The system is capable of controlling a maximum of 200 RSCs. At the remote sites, the RSCs can be hard wired together in a bus topology using a shielded pair. The MCU can communicate with these buses via hard wire, conventional radio, trunked radio, or dial telephone. Hard wire MCU links require the use of RS-485 interface cards, each capable of controlling a maximum of 50 RSCs. The system is not capable of handling heterogeneous communication media simultaneously.

RSCs can control up to 48 stations and can be equipped with a flow meter. The front panel user interface features LED displays, dials and function keys. Programming information can be protected by use of an optional access code. The controllers are capable of stand-alone operation and also can be manually operated with a hand held radio unit. A default program provides minimum watering in case of regular program loss (which may happen, for example, in the event of power loss and backup battery failure).

The optional Sentinel board provides electrical, pressure loss, and excess moisture fault detection. When a fault of the first two types is detected, the currently active station is bypassed, and a record of the fault is made in memory. The faulty station remains inactive until the fault is cleared by a reset. Excess moisture faults need not be cleared as the controller will perform a check at each scheduled run time.

An optional Master Valve Control board is available to provide protection against catastrophic main line pressure losses.

MCU Software

The MCU software is menu driven, password protected and provides on-line help, but does not support a mouse or graphics. It refers to RSCs as "clocks."

Program files specify irrigation for a four week period. Six start times per day are allowed, with up to 127 distinct station run times each. Station run times can be copied and entered in any order. Pauses between station run times are implemented by assigning a run time to dummy station 0. Total watering time and end time are computed and displayed as the user enters the program. There is a limit of 3556 distinct station run times per program. Schedules for days and weeks can be copied as well. Program files can be downloaded to and uploaded from the RSCs. Program files can be named and saved to disk.

Information about RSCs is kept in clock files. This includes phone number (if applicable), address, the number of stations, Sentinel board installation indicator, flow meter factor (if installed), location, and station flow rate data.

The clock status screen enables the user to monitor RSC status information and to effect manual control. The status information for an RSC includes: total flow rate, current operating mode, current watering station, current station flow rate (from clock file), current start time, remaining watering time, current day and week of schedule, water budget factor value, and Sentinel status. Information for several RSCs can be requested at the same time, but it must be refreshed manually.

Manual operations include setting the water budget factor, syringing, setting the RSC operating mode, putting the controller in rain hold for a specified number of days, clearing Sentinel faults, overriding the Sentinel board, and setting the time.

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Several reports are available. The "Schedule vs. Window" report displays stations scheduled to operate outside a specified time window. The "Peak Flow Rate" report displays daily peak flow rate data. The "Water Meter Readings" report accumulated water meter readings gathered from the clock status screen. The "Program Differences Report" can be used to the differences between any two programs. Finally, the "Sentinel Fault" report displays a list of faults grouped by controller; again, the information reported must be gathered first from the clock status screen.

Valcon's V-III provides simple and flexible means of implementing time based irrigation programming and status monitoring. However, it lacks group programming features, continuous real time monitoring capabilities, data acquisition and ET driven adjustments.

Valcon has recently announced plans to supersede V-III with an upcoming system called VAC, which is still under development. We now present a brief summary of VAC's current specifications.

Valcon's VAC will feature time based programming, sensor based programming, water budgeting, infiltration rate compensation, moisture sensing, data acquisition and monitoring, a variety of communication interfaces, radio communications, distributed intelligence, and password protection.

VAC controllers will be able to control up to 48 stations providing each with a master valve output. The controllers will be capable of stand alone operation and local programming. Central control will be supported via hard wire, dial telephone, and radio communications. Each controller will be capable of supporting one of each of the following types of sensors: wind, rain, and flow; also, support will be provided for up to 10 moisture sensors. Their user interface will consist of an LCD display and a 24 button keypad.

Time based programming will be supported for up to 10 station groups having a single start time that will be schedulable in a variety of ways, including a variable length irrigation cycle of up to 30 days. Station on times will be individually defined and station groups will support definition of up to 10 soak cycles. The sensor inputs will provide feedback to suspend irrigation in case of high wind speed, rain, flow faults and excessive moisture. Station groups will be able to run sequentially or concurrently. Up to 24 programmable irrigation suspension events will be supported.

3.3.14 Valcon's VIP

Valcon's VIP system is designed for irrigation management in highway, municipality, park systems, and golf course applications. It features water budgeting, infiltration rate compensation, moisture sensing, data acquisition and monitoring, a variety of communication interfaces, radio communications, manual operation with a hand held radio unit, distributed intelligence, and foreign language support. It should be noted that this survey is based on marketing brochures and not on an actual review of the software. This is because the manufacturer was not able to provide a working version of the software and proper documentation in time for the preparation of this report.

The MCU is based on a Macintosh computer and requires Hypercard 2.0 to run. The only centrally accessible features are water budgeting, syringing, manual station operation, rain hold, acquisition of sensor data and report generation. The controllers feature a user interface consisting of an LCD display screen and a keypad, local operation is aided by screen prompts

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Time based programming is available locally only and allows station group programming in terms of start times and run times.

3.3.15 System Information

This section presents summary information for the Remote Irrigation Control (RIC) systems surveyed in this report. This summary includes system features, system pricing, and manufacturer contacts.

The RIC system features, presented in table 3.1, cover the system's intended design applications, irrigation-specific programming features, data acquisition, communications and utility functions. The reader must be aware that the actual implementation of these features generally differs from system to system and should refer to the system surveys for more details.

To gather the system pricing information, each manufacturer was requested to provide price information for the following "start up" system.

1) A main control unit with everything necessary to control twenty (20) remote sites via conventional radio. It should include the system software, the computer, a printer, any interface equipment, any necessary radio equipment, antennas, enclosures, etc. In short, everything that would be needed at the control point. Assume that a radio repeater will not be needed.

2) The field equipment necessary to provide irrigation control to twenty (20) geographically separate remote sites via conventional radio. Each site will have the need to control 24 stations. As before it should include the controllers, any interface equipment, any necessary radio equipment, antennas, enclosures, etc. Do not include any of the costs associated with the hydraulic system (valves, etc.). Additionally, assume that this is a basic "start up" system and that none of the system's data acquisition features (flow monitoring, etc.) will be used initially.

3) The weather monitoring equipment necessary to provide complete evapotranspiration information from a single site. This site is to be linked to the main control point via a hard wire connection (with "short haul" modems). Also, include the price of all associated equipment necessary to implement the weather station.

The response from each manufacturer is summarized in table 3.2.

The costs are divided into four areas: Main Control Unit (MCU), remote site equipment, weather station, and installation. The summarized prices include all software, interfaces, cables, antennas, and enclosures required for operation. The costs of hydraulic equipment are not included and the installation costs listed are limited to system start up and operational verification, except as noted elsewhere. Any ongoing costs associated with the Communication Link (CL) or weather station are not included. The site equipment column lists the price for a single site and the last column lists the total system cost. Prices do not include applicable sales taxes.

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This information provides benchmark cost figures for RIC system comparison. The reader should be aware of several caveats. First, not all systems surveyed fit the full RIC model; particularly, some do not feature an MCU. Second, not all systems feature radio Communication Links; the exceptions to this requirement show dial telephone link prices. Third, weather station prices are given only for those systems providing integrated weather station support. Fourth, actual installation costs may vary from site to site once additional materials are included; typical installations are performed by contractors not directly associated with the manufacturers of the RIC system. Fifth, considerable discounts from list prices are provided by some distributors of RIC systems.

Finally, a list of RIC system manufacturer contacts is presented in table 3.3

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Table 3.1 Summary of RIC System Features

	Buckner COPS Universal	Griswold IDC Central	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini Mark	Toro Network 8000	Aquametrics COM-1	Buckner COPS Genesis	NSC Control	Rain Master Evolution	Solar Wind System 390-B	Thompson Mark-1	Valcon V-III	Valcon VIP
Full Central Control	O	O	O	O	O	O		O		O	O	O	O	
Highway applications	O	O	O	O	O	O	O	O	O	O			O	O
Municipality applications	O	O	O	O	O	O	O	O	O	O			O	O
Park systems applications	O	O	O	O	O	O	O	O	O	O			O	O
Golf course applications	O	O	O		O	O	O	O	O	O	O	O	O	O
Time based programming	O	O	O	O	O	O	O	O		O	O	O	O	O
Volume based programming			O											
Sensor based programming			O	O										
Filter and fertilizer programming			O											
Water budgeting	O	O	O	O	O	O		O	O	O	O	O	O	O
ET driven irrigation			O	O	O	O						O		
Flow optimization				O	O	O						O		
Soil model based adjustments				O		O								
Infiltration rate compensation				O		O	O			O				O
Moisture sensing					O		O			O		O	O	O
Extensive environmental adjustment factors						O								
Data acquisition and monitoring		O	O	O	O	O	O				O	O	O	O
Integrated weather station support			O	O	O	O		O				O		
Alarm response definition			O	O		O								
Alarm paging			O											
Hard wire interface		O	O	O	O	O		O			O	O	O	O
Radio interface	O	O	O	O	O	O	O		O	O	O	O	O	O
Trunked radio interface			O	O									O	
Cellular telephone interface		O		O	O	O	O			O		O		
Dial telephone interface		O		O	O	O	O	O		O	O	O	O	O
Private line telephone interface			O			O								
Manual operation with hand held radio unit	O	O	O	O	O					O	O	O	O	O
Distributed intelligence		O	O	O	O	O		O		O		O	O	O
Multitasking			O		O					O		O		
Graphical user interface					O	O				O		O		O
Extensive reporting capabilities			O	O	O	O								
Data export support					O							O		
Password protection		O	O	O									O	
Foreign language support		O	O	O	O	O						O		O

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Table 3.2 Remote Irrigation Control System Prices

System	MCU	Site Equipment	Weather Station	Installation	20-site System
Buckner COPS Universal	$11,200	$2,220	Not Applicable	Included in system price	$55,600
Griswold IDC Central	$15,483	$4,668	Not Applicable	Included in system price	$108,843
Motorola MIR 5000****	$23,616	$5,820	$6,298	$6,775	$153,089
Rain Bird Maxicom****	$30,140	$5,021	$13,140	$4,000	$147,700
Thompson Mini-Mark****	$24,910	$5,300	$16,000	Included in system price	$146,910
Toro Network 8000****	$36,411	$7,000	$9,600	Included in system price	$186,011
Aquametrics COM-1***	Not Applicable	$6,203*	Not Applicable	Included in system price	$122,060
Buckner COPS Genesis***	$10,300	$1,500	$5,500	Included in system price	$45,800
NSC Control**	Not Applicable	$810	Not Applicable	$4,000	$20,200
Rain Master Evolution	$23,261	$4,286	Not Applicable	Included in system price	$108,981
Solar Wind System 390-B	$27,045	$6,960	Not Applicable	Unavailable	$166,245
Thompson Mark-1	Unavailable	Unavailable	Unavailable	Unavailable	Unavailable
Valcon VIII	Unavailable	Unavailable	Unavailable	Unavailable	Unavailable
Valcon VIP	Unavailable	Unavailable	Unavailable	Unavailable	Unavailable

* Aquametrics Com-1 uses moisture sensing as an integral part of its operation. Therefore, the price of moisture sensing devices is included with the site equipment.

** Network Services Control requires a $15.90 use fee, per month, per RSC, for operation.

*** Radio link price is not available, pricing shown is for dial telephone connection.

**** System meets all requested specifications.

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Table 3.3 RIC System Manufacturer Reference

System	Company	Contact	Phone Number
COPS Universal COPS Genesis	Buckner 4381 Brawley Avenue Fresno, CA 93722	Kurt Thompson National Sales-Golf	(209) 275-0500 Corporate office (209) 276-7829 Home office
IDC Central	Griswold Controls 2803 Barranca Road Irvine, CA 92714	Stephen W. Sawdon General Manager	(714) 559-6000 Corporate office
MIR 5000	Motorola 9912 Business Park Drive, Suite 130 Sacramento, CA 95827	Eric Scott Area Sales Engineer, Electronic Command and Control Systems	(916) 854-2800 District office (916) 854-2813 Direct line
Maxicom Maxicom Jr.	Rain Bird 145 North Grand Avenue Glendora, CA 91740-2469	Sally Prusia Maxicom Technical Specialist	(818) 963-9311 Corporate office (714) 981-1489 Home office
Mini-Mark MarK 1	Thompson Manufacturing Co. 5075 Edison Avenue P.O. Box 1500 Chino, CA 91708	Jack Kincaid District Sales Manager, Commercial Products Division	(714) 591-4851 Corporate office (510) 706-2342 Home office
Network 8000	The Toro Company, Irrigation Division 5825 Jasmine Street Riverside, CA 92504-1183	Jon Williams Product Manager, Golf Marketing & Sales	(714) 688-9221 Corporate office (714) 785-3392 Direct line
COM-1	Aquametrics Inc. 7764 Arjons Drive San Diego, CA 92126-4365	C. Michael Ruscoe Northwestern Regional Manager	(619) 693-8182 Corporate office (408) 338-7037 Home office
NSC Control	Network Services Corporation 561 Sky Ranch Drive Petaluma, CA 94954	Michael Marian Vice-President	(707) 769-9696 Corporate office
Evolution	Rain Master 5290 N. Valentine, #201 Fresno, CA 93711	Nick M. Dvorak Director, Sales/Marketing	(209) 276-8450 Corporate office
System 390-B	Solar Wind Systems, Inc. 37 Commercial Boulevard Novato, CA 94947	Michael Marian President	(415) 883-0404 Corporate office
V-III VIP	Valcon Automatic Irrigation Equipment Company 10837 Central Avenue South El Monte, CA 91733	Robert Goldman Chief Executive Officer	(818) 444-5466 Corporate office

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3.4 Benchmark Results

This section introduces the results of the RIC system benchmarks. Of all the systems surveyed, only six are benchmarked. The criteria for inclusion in the benchmarks are: 1) that the system provides full centralized control as described by our model; 2) that the system supports Communication Link technology adequate to cover typical Caltrans highway landscape sites; 3) that the MCU software is generic enough to be applicable to Caltrans highway landscape irrigation applications (as opposed to golf course-oriented systems); and 4) that the system was available as a final product as of January 1, 1992, and that it is expected to be available in the future.

The six systems to meet these criteria are: Buckner's COPS Universal, Griswold's IDC Central, Motorola's MIR 5000, Rain Bird's Maxicom, Thompson's Mini Mark, and Toro's Network 8000. Aqua Metrics' COM 1 does not fit our full RIC model and neither does Network Services Control. Both Rain Master's Evolution and Buckner's COPS Genesis were in beta testing at the time of the inclusion deadline. Solar Wind's System 390-B and Thompson's Mark-1 fall in the category of being too golf course-oriented to be included in the benchmarks. Valcon's V-III met all the criteria except that it is being superseded with a new system called VAC and there is no accurate technical information available.

The benchmark results are now presented in table form. The first set of tables present the results for the Main Control Unit (MCU) feature group and the second set of tables present the results for the Remote Site Controller (RSC) feature group.

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Remote Irrigation Control System Benchmark Features - Main Control Unit (MCU)

Company Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
MCU Control and Display						
❑ Maximum number of RSCs controlled	999	9993	8000	200	100	800
• Largest existing system	40 RSCs	68 RSCs	180 RSCs	50 RSCs	Zero RSCs	81 RSCs
❑ Maximum number of stations controlled	1500	479664	416000	134400 w/o inputs	3600	25600
❑ Irrigation programmable by grouped station number	No	No	No	No	Yes	Yes
❑ Irrigation programs storable and retrievable from MCU permanent storage	Yes	Yes	Yes	Yes	Yes	Yes
❑ Irrigation programs transferable from RSC to MCU	No	Yes	Yes	Yes, MCU originated programs only	Yes	Yes
❑ Irrigation programs transferable from MCU to RSC	No	Yes	Yes	Yes	Yes	Yes
❑ Irrigation programs transferable from one RSC to another via the MCU	No	No	Yes	No	No	No
❑ Confirmation promot used for accepting major setting or irrigation program changes	Partial	No	Yes	No	No	No
❑ Programmable download time for irrigation programs	No	Yes	Yes	Yes, for entire RSC only	Yes	Yes
❑ Programmable irrigation program execution suspension	No	No	Yes	Yes	No	No
• Immediate irrigation program execution suspension	Yes	Yes	Yes	Yes	Yes	Yes
❑ Assignment of a "default" irrigation program for RSC on system start/reset	Yes, for reset only	No	No	No	No	No
❑ Notification of alarm from RSC when RSC irrigation program is changed on site	No	Yes	Yes	No	No	Yes, through status screen
❑ Assignment of program/routine to be executed in response to a specified alarm	No	No, not at MCU	Yes	No	Yes, rain shutdown only	Yes, for predefined set of routines
• User defined actions are downloadable to RSC	No	No	Yes	Yes	No	No
❑ Separate screen display for "alarm warnings"	Yes, to printer only	Yes	Yes	Yes	Yes	Yes
• Grouped by RSC	Yes	Yes	Yes	No	No	Yes
• Grouped by stations	No	No	No	No	No	No
• Grouped by area	No	No	Yes	No	No	Yes
• Time stamped	Yes	Yes	Yes	Yes	Yes	Yes
• Hard copy report	Yes	Yes	Yes	Yes	Yes	Print screen only
❑ Separate screen display for summary	Yes	No	Yes	No	No	No
• Summary display of RSC status and conditions	Yes	No	Yes	Yes	No	No
❑ Separate screen display of intended vs. actual irrigation history	No	Yes	Yes, by comparing two screens	Yes, by comparing two screens	No	Yes, by comparing two screens
• Grouped by RSC	No	Yes	Yes	Yes	No	Yes
• Grouped by stations	No	No	No	No	No	No
• Grouped by area	No	No	No	No	No	Yes
• History length	No	365 days	One day	Information not available	No	Limited by MCU hard drive storage only
• Hard copy report	No	Yes	No	No	No	Yes, print screen only
❑ Simultaneous access of all RSCs for system start up/shutdown	No	Yes	Yes	No	Yes	Yes
❑ MCU password protection	No	No	Yes	Yes	Yes, through operating system only	No
❑ Assignment of new RSC local password via MCU	No	Yes	No	No	No	Yes, for dial telephone RSCs only
• System wide	No	No	No	No	No	No
• By RSC	No	Yes	No	No	No	Yes, for dial telephone RSCs only
MCU Irrigation Program						
❑ Access to all RSC irrigation scheduling features	No	Yes	Yes	Yes	No	Yes
❑ Station "on time" adjustment by percent multiplier	Yes	Yes	Yes	Yes	Yes	Yes
• Adjustment by station group	No	No	Yes	Yes	Yes	Yes
• Adjustment by RSC group	No	Yes	Yes	Yes	No	Yes
• System wide adjustment	Yes	Yes	Yes	No	No	Yes
• Preservation of original irrigation program at RSC	No	Yes	Yes	No	Yes	No
❑ Irrigation program adjustment based on evapotranspiration rate	No	No	Yes	Yes	Yes	Yes
• Grouped by area	No	No	Yes	Yes	No	No
• Manual entry	No	No	Yes	Yes	Yes	Yes
• Automatic entry	No	No	Yes	Yes	Yes	Yes
•• Value averaging	No	No	Yes	Yes	Yes	Yes
• Evapotranspiration rate adjustment factor.	No	No	Yes	Yes	Yes	Yes
• Soil model based adjustment factor.	No	No	No	Yes	No	Yes
❑ Theoretical "on time" flow projection	No	No	No	Yes	No	Yes
❑ Fine adjustment of start time	No	No	No	Yes, through irrigation program only	No	Yes
❑ Fine adjustment of water shutdown delays	No	No	No	Yes, through irrigation program only	No	No

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Remote Irrigation Control System Benchmark Features - Main Control Unit (MCU)

Company Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
MCU Data Acquisition						
❑ Maximum number of analog data acquisition inputs	Zero	79944 w/o pulse or digital inputs	Zero	Zero	Zero	1600
• Threshold alarm	No	Yes	No	No	No	Yes, pressure & temparature only
• Data value monitoring	No	No, not at MCU	No	No	No	Yes, pressure & temparature only
• Data labeling	No	No	No	No	No	No
• Data scaling	No	No	No	No	No	No
• Data manipulation	No	No	No	No	No	No
•• Arithmetic combination of multiple inputs	No	No	No	No	No	No
• Threshold point setting	No	No, not at MCU	No	No	No	Yes, pressure & temparature only
• Data display	No	No, not at MCU	No	No	No	Yes, pressure & temparature only
•• Display of user defined analog sensor readings	No	No	No	No	No	Yes, pressure & temparature only
•• Text mode	No	No	No	No	No	Yes, through external program only
•• Graphics mode	No	No	No	No	No	Yes
• Permanent data storage	No	No	No	No	No	Yes
•• Manual	No	No	No	No	No	No
•• Automatic	No	No	No	No	No	Yes
••• Variable upload frequency	No	No	No	No	No	Yes
• Hard copy report	No	No	No	No	No	Yes, print screen only
❑ Maximum number of pulse (rate) data acquisition inputs	Zero	79944 w/o analog or digital inputs	224000 w/o digital inputs	5600 w/o controllers	100, flow only	9600, w/o digital inputs
• Pulse (rate) alarm	No	Yes, flow only	No	No	Yes, flow only, fixed limits	Yes, flow, wind speed, & rain only
• Pulse (rate) monitoring	No	No	Yes	Yes, flow & pulses only	Yes, flow only	Yes, flow, wind speed, & rain only
• Data labeling	No	No	Yes	No	No	Yes, flow, wind speed, & rain only
• Data scaling	No	No	Yes	Yes, flow only	No	Yes, flow, wind speed, & rain only
• Data manipulation	No	No	No	Yes, flow & pulses only	No	No
•• Arithmetic combination of multiple inputs	No	No	No	Yes, flow & pulses only	No	No
• Threshold point setting	No	No, not at MCU	Yes	Yes	No	Yes, flow, wind speed, & rain only
• Data display	No	No, not at MCU	Yes	Yes, flow only	Yes, flow only	Yes, flow, wind speed, & rain only
•• Display of user defined pulse (rate) sensor readings	No	No	Yes	No	No	Yes, flow, wind speed, & rain only
•• Text mode	No	No	Yes	No	Yes, flow only	Yes, through external program only
•• Graphics mode	No	No	Yes	Yes, flow only	No	Yes
• Permanent data storage	No	No	Yes	Yes	Yes, flow only	Yes
•• Manual	No	No	No	Yes	Yes, flow only	No
•• Automatic	No	No	Yes	No	Yes, flow only	Yes
••• Variable upload frequency	No	No	Yes	No	No	Yes
• Hard copy report	No	No	Yes	Yes	Yes, flow only	Yes, print sreen only
❑ Maximum number of digital data acquisition inputs	Zero	79944 w/o analog or pulse inputs	224000 w/o pulse inputs	5600 w/o controllers	500, rain switch & moisture sense only	9600, w/o pulse rate input
• State alarm	No	Yes	No	No	Yes, rain switch & moisture sense only	Yes
• State monitoring	No	No	Yes	Yes	Yes, rain switch	Yes
• Data labeling	No	No	Yes	No	No	Yes
• Data manipulation	No	No	Yes	No	No	No
•• Boolean combination of multiple inputs	No	No	Yes	No	No	Yes
• Data display	No	No	Yes, text only	Yes	Yes, rain switch only	Yes
•• Display of user defined digital sensor readings	No	No	Yes, fixed format only	No	No	Yes
•• Text mode	No	No	Yes	No	Yes, rain switch only	Yes
•• Graphics mode	No	No	No	No	No	No
• Permanent data storage	No	No	Yes	Yes	No	Yes
•• Manual	No	No	No	Yes	No	No
•• Automatic	No	No	Yes	No	No	Yes
••• Variable upload frequency	No	No	Yes	No	No	Yes
• Hard copy report	No	No	Yes	Yes	Yes, rain switch & moisture sense only	Yes, print sreen only
❑ Maximum number of system wide status queries per day per RSC to MCU	Zero	One, automatic	1440	One, automatic	Information not available	Continuious polling
• Variable status query frequency	No	No	Yes	No	Information not available	Yes
• Average time for status query per RSC	No	90 sec.	15 sec. to 45 sec.	30 sec. to 4 min.	Information not available	10 sec.

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Remote Irrigation Control System Benchmark Features - Main Control Unit (MCU)

Company / Product	Buckner / COPS Universal	Griswold / IDC	Motorola / MIR 5000	Rain Bird / Maxicom	Thompson / Mini-Mark	Toro / Network 8000
MCU to RSC Communication Link Hardware						
❑ Two way communications with RSC	Yes	Yes	Yes	Yes	Yes	Yes
❑ Simultaneous support of multiple transmission media	No	Yes	Yes	Yes	Yes	Yes
❑ Hard wire interface	No	Yes	Yes	Yes, for single RSC system only	Yes	Yes
• Minimum number of signal wires required	N/A	One pair	One pair, #14-2 UF	RS-232C commection	One twisted Pair	One Pair
• Shielded cable required	N/A	No	No	No	No	Yes
• Simple interconnect engineering	N/A	No	Yes	Yes	Yes	Yes
• Reduction of hard wire distance to the MCU for each RSC	N/A	Semi-bus topology	Bus topology	Point to point topology	Semi-bus topology	Ring topology recommended, can be bus
• Maximum signal cable length	N/A	Two miles w/ 65 RSCs, w/o repeater	Six miles	50 feet	5000 ft. w/o repeater	Five miles
❑ Radio interface	Yes	Yes	Yes	Yes	Yes	Yes
• Return channel capability	Yes	Yes	Yes	Yes	Yes	Yes
• RF carrier sensing capability	No	No	Yes	No	No	No
❑ Trunked radio interface	Yes	No	Yes	Yes	No	No
❑ Cellular telephone interface	No	Yes	No	Yes	Yes	Yes
❑ Dial telephone interface	No	Yes	No	Yes	Yes	Yes
❑ Private line telephone interface	No	Yes	Yes	Yes	Yes	Yes
• 2-wire circuit	No	Yes	Yes	Yes	Yes	Yes
• 4-wire circuit	No	No	No	No	No	No
MCU to RSC Communication Link Software						
❑ Information transfer error checking	Yes	Yes	Yes	Yes	Yes	Yes
• Single direction, multiple transmission with parity or checksum	No	No	No	No	No	No
• Dual direction transmission with acknowledge and checksum	No	Yes	No	Yes	No	No
• More sophisticated error checking	Yes	No	Yes	No	Yes	Yes
❑ Communications equipment failure feedback	Yes	Yes	Yes	Yes	Yes	Yes
• Data integrity alarm	No	No	Yes	Yes	No	Yes
• Transmission failure alarm	Yes	Yes	Yes	Yes	Yes	Yes
• Failure log in summary display	No	No	Yes	No	No	Yes, in alarm screen only
❑ Communication can be initiated by MCU and RSC	No	No	Yes	No	No	No
❑ Interface to different models of RSC of the same vendor	Yes	No	Yes	Yes	Yes	Yes
MCU Computer Requirements						
❑ Minimum computer requirement	IBM PC, AT, or equivalent	IBM PC, AT, or equivalent	IBM PS/2	IBM PS/2 Model 50, or equivalent	Apple Macintosh Classic II	IBM PC, AT, or Equivalent
❑ "Off-the-shelf" computer configuration	Yes	Yes	Yes	Yes	Yes	Partial
❑ Operating system requirement	MS-Dos	MS-Dos	MS-Dos	MS-Dos	Macintosh 7 & Hypercard 2.0	MS-Dos
❑ Minimum RAM requirement	640 K Bytes	512 K Bytes	Four M Bytes	640 K Bytes	Two M Bytes	Four M Bytes recommended
❑ Hard drive requirement	20 M Bytes	10 M Bytes space	10 M Bytes space	No	40 M Bytes	120 M Bytes recommended
❑ Color Monitor/Card required	Yes	Yes	Yes	No	No	Yes

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Remote Irrigation Control System Benchmark Features - Main Control Unit (MCU)

Company Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
MCU Utility, Peripheral and Related Functions						
❑ Terminology used throughout software user interface	Generic	Generic	Generic	Generic	Generic	Generic
❑ Operation of the MCU via modem with a second computer	No	Yes, w/ user supplied software & modem	Yes, w/user provided software & modem	Yes, w/user provided software & modem	Yes, w/user provided software & modem	Yes, w/user provided software & modem
❑ Alarm condition paging	No	No	Yes	No	No	No
❑ MCU need not be present after download	No	Yes	Yes	Yes	Yes	Yes
❑ Background tasking of system program	No	No	Yes	No	Yes	Yes
❑ Weather station interface	No	No	Yes	Yes	Yes	Yes
• Maximum number of weather stations system will support	Zero	Zero	Six	Eight	One	One
• Seamless interface	No	No	Semi	Semi	Yes	Semi
• Complete evapotranspiration rate data	No	No	Yes	Yes	Yes	Yes
• Hard wire interface	No	No	Yes	Yes	Yes	Yes
• Radio interface	No	No	Yes	No	Yes	No
• Trunked radio interface	No	No	No	No	No	No
• Cellular telephone interface	No	No	Yes	Yes	No	No
• Dial telephone interface	No	No	Yes	Yes	Yes	No
• Private line telephone interface	No	No	Yes	Yes	No	No
❑ California Irrigation Management Information System (CIMIS) interface	No	No	Yes	No	No	Yes
• Seamless interface	No	No	Semi	No	No	Semi
❑ Menu driven operation	Yes	Yes	Yes	Yes	Yes	Yes
❑ Context sensitive help	Yes	Yes	Yes	Partial	No	Yes
❑ Program and data storage on floppy disk	Yes	No	No	Yes	No	No
❑ Multiple display mode support	Yes	No	No	Yes	Yes	Yes
❑ MCU program in color	Yes	Yes	Yes	Yes	No	Yes
❑ Graphics printer support	No	No	Yes	Yes	Yes	Yes
❑ Screen saver	Yes	Yes	Yes	No	No	No
❑ Optional mouse support	No	No	Yes, required	No	Yes, required	Yes
❑ Foreign language support	No	No, not at MCU	Yes, Spanish, Hebrew & Italian	Yes, French & Japanese	No	Yes, French
MCU Supports						
❑ Easy to learn software	Yes	Yes	Moderate	No	Yes	Moderate
❑ Free technical support	Yes	Yes	One year	Yes	Yes	Yes
❑ Free on-site system analysis	Yes	Yes	Yes	Yes, for two years	Yes	No
❑ Free software updates	Yes	Yes	Yes	Yes	Yes	No
❑ Upgrade continuity between hardware and software	Yes	Yes	Yes	Yes	Yes	Yes, for most upgrades

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Remote Irrigation Control System Benchmark Features - Remote Site Controller (RSC)

Company Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
RSC Control and Display						
❑ Maximum number of independently accessible stations	42	48	52	672	36	32
• Maximum rms current output per station at 24 Vac	One ampere	1.1 amperes	Two amperes	2.5 amperes	1.8 amperes	0.6 amperes
• Maximum total rms current output at 24 Vac	Dependent on existing clock/controller	2.5 amperes	Six amperes	2.5 amperes	11.25 amperes	3.6 amperes
❑ Station circuit short indicator	No	Yes	Yes, for MIR 5000F - DC only	No	No	Yes
• Shorted station(s) disabled automatically	No	Yes	Yes, for MIR 5000F - DC only	No	No	No
• Shorted station(s) logged automatically	No	Yes	No	No	No	Yes, at MCU only
• Alarms MCU indicating station short	No	Yes	Yes, for MIR 5000F - DC only	No	No	Yes
❑ Station circuit open indicator	No	Yes	Yes, for MIR 5000F - DC only	No	No	Yes
• Open station(s) disabled automatically	No	Yes	Yes, for MIR 5000F - DC only	No	No	No
• Open station(s) logged automatically	No	Yes	No	No	No	Yes, at MCU only
• Alarms MCU indicating station open	No	Yes	Yes, for MIR 5000F - DC only	No	No	Yes
❑ Pump start / master valve circuit	Yes	Yes	Yes	Yes	Yes	Yes
❑ Programmable irrigation program execution suspension	No	No	Yes	Yes, at MCU only	No	No
• By day of the week	No	No	No	Yes	No	No
• By date	No	No	Yes	No	No	No
• By time of day	No	No	Yes	Yes	No	No
• Locally programmable	No	No	No	No	No	No
• Downloadable from MCU	No	No	Yes	Yes	No	No
•• Locally stored and executed	No	No	No	Yes	No	No
❑ Manual operation via hand held radio	Yes	Yes	Yes	Yes	Yes	No
• Through MCU	No	No	Yes	No	No	No
• Radio unit on RSC	Yes	Yes	No	Yes	Yes	No
❑ Manual operation without disrupting irrigation program	Yes	Yes	Yes	Yes	Yes	Yes
❑ Assignment of the same irrigation program to all stations	Yes, at MCU only	Yes	Yes	Yes, at MCU only	No	No
❑ Assignment of an existing station irrigation program to other station(s)	Yes, at MCU only	Yes	No	No	No	Yes
❑ Irrigation program(s) downloadable from the MCU	No	Yes, at MCU only	Yes	Yes, at MCU only	Yes	Yes
❑ Irrigation program(s) uploadable to the MCU	No	Yes, at MCU only	Yes	Yes, at MCU only	Yes	Yes
❑ Maximum number of different irrigation programs storable in non-volatile memory	99, stored at MCU only	48	60	999	72	12 at RSC / 16 at MCU
❑ Maximum number of days of actual irrigation history storable in non-volatile memory	Zero at RSC	45 days at RSC	Zero at RSC	Seven days at RSC	Zero at RSC	One day at RSC
❑ Menu driven format for command and display	No operator access at RSC	Yes	Yes	Partial command set, ISC only	Yes	Yes
❑ Access to irrigation program and other critical functions is password protected	No operator access at RSC	Yes	No	No, not at RSC	No	No
❑ Assignment of new RSC local password via MCU	No operator access at RSC	Yes	No	No	No	Yes, from dial telephone RSCs only
❑ Confirmation prompt used for accepting major setting or irrigation program changes	No operator access at RSC	Yes, at RSC only	No	No	No	No
❑ Alarm MCU when the irrigation program has been locally altered	No operator access at RSC	Yes	Yes	No	No	Yes
RSC Stand Alone Capability						
❑ Autonomous execution of RSC timing, irrigation program and control features	No	Yes	Yes	Yes	Yes	Yes
• Maximum duration of autonomous operation	N/A	Indefinite	Indefinite	Seven days	Indefinite	Indefinite

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Remote Irrigation Control System Benchmark Features - Remote Site Controller (RSC)

Company / Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
RSC Irrigation Program						
❑ Access to all scheduling features accessible from MCU	No	Yes	Yes	No	Yes	Yes
❑ Maximum duration of station "on time"	9 hr. 59 min.	9 hr. 59 min. 59 sec.	99 hr. 59 min.	24 hr. from MCU / 9.9 hr. from RSC	255 min. from MCU / 255 hr. from RSC	Four hr.
• Resolution of station "on time"	One min.	One sec.	One sec.	One sec. from MCU / One min. from RSC	One min. from MCU / One sec. from RSC	One sec.
• Number of station "on times" per twenty four hour period	1440	Eight	5940	Unlimited from MCU / Eight from RSC	192	384
• Variable "on time" durations within any twenty four hour period	Yes, at MCU only	Yes	Yes	Yes from MCU / No from RSC	No	Yes
• Set "on time" by start time and duration	Yes, at MCU only	Yes	Yes	Yes	Yes	Yes
• Set "on time" by start and stop times	No	No	No	No	No	No
• Set "on time" by volume	No	No	Yes	No	No	No
• Set "on time" by precipitation	No	No	No	No	No	No
❑ Maximum number of days in the irrigation cycle	Seven, at MCU only	31	60	99 from MCU / 16 from RSC	Seven days from MCU / 99 days from RSC	30
• Variable cycle period	No	Yes	Yes	Yes	Yes, at RSC only	Yes
❑ Station "on time" adjustment by percent multiplier	Yes, at MCU only	Yes	Yes	Yes	Yes	Yes
• Preservation of original RSC irrigation program	Yes, at MCU only	Yes	Yes	No	Yes	No
• Range of adjustment	0% to 599%	0% to 300%	0% to 999%	1% to 999% from MCU 25% to 200% from RSC	0% to 255%	2% to 900%
• Resolution of adjustment	1%, at MCU only	1%	1%	1% increments from MCU 25% increments from RSC	1%	1% increment
❑ Infiltration rate/slope compensation	No	No	No	Yes, at MCU only	No	Yes
• By station	No	No	No	Yes	No	Yes, at MCU only
❑ Flow driven scheduling	No	No	No	Yes, at MCU only	No	Yes, at MCU only
❑ Fine adjustment of water shutdown delay	No	No	No	Yes, at MCU only	No	No
❑ Fine adjustment of station start time	No	No	No	Yes, at MCU only	No	Yes
RSC Data Acquisition						
❑ Maximum number of analog data acquisition inputs	Zero	Eight w/o pulse or digital inputs	Zero	Zero	Zero	Two
• Additional circuitry required for analog data acquisition	N/A	Yes	N/A	N/A	N/A	No
• Data value monitoring	No	No	No	No	No	Yes, pressure & temparature only
• Data labeling	No	No	No	No	No	No
• Data scaling	No	No	No	No	No	No
• Threshold point setting	No	Yes	No	No	No	Yes, accessible from MCU only
❑ Maximum number of pulse (rate) data acquisition inputs	Zero	Eight w/o analog or digital inputs	28 w/o digital inputs	28 w/o controllers	One, flow only	Six, w/o digtal inputs
• Additional circuitry required for pulse (rate) data acquisition	N/A	Yes	No	Yes	Yes, flow only	Yes
• Pulse (rate) monitoring	No	No	Yes, flow only	No, not at RSC	Yes, flow only	Yes, flow, wind speed, & rain only
• Pulse (rate) alarm	No	Yes, flow only	Yes, flow only	Yes, accessable from MCU only	Yes, flow only	Yes, accessible from MCU only
• Data labeling	No	No	No	No	No	No,not at RSC
• Data scaling	No	No	Yes, flow only	No	No	Yes
• Threshold point setting	No	Yes	Yes	Yes, accessable from MCU only	No	Yes, accessible from MCU only
❑ Maximum number of digital data acquisition inputs	Zero	Eight w/o analog or pulse inputs	28 w/o pulse inputs	28 w/o controllers	Five, rain switch & moisture sense only	Six, w/o pulse rate inputs
• Additional circuitry required for digital data acquisition	N/A	Yes	No	Yes	Yes	Yes
• State monitoring	No	Yes	Yes	No, not at RSC	Yes, rain switch & moisture sense only	Yes
• State alarm	No	Yes	Yes	Yes, accessable from MCU only	Yes, rain switch only	Yes
• Data labeling	No	No	No	No	No	No, not at RSC
❑ Non-volatile data storage	No	Yes	No	Yes	No	Yes
• Maximum number of data points	N/A	20160	Zero	672	N/A	20160

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Remote Irrigation Control System Benchmark Features - Remote Site Controller (RSC)

Company Product	Buckner COPS Universal	Griswold IDC	Motorola MIR 5000	Rain Bird Maxicom	Thompson Mini-Mark	Toro Network 8000
RSC to MCU Communication Link Hardware						
❑ RSC telecontrollable without the addition of circuitry	Yes	No	Yes	No	No	Yes
❑ Signal line surge protection	No, hard wire not available	Yes	Yes	Yes	Yes	Yes
FCU to FSCU Communication Link Hardware						
❑ FCU and FSCU are an integrated unit	Yes	Yes	Yes	No, FCU & FSCU are seperate	Yes	Yes
❑ Hard wire interface available	No	No	Yes	Yes	No	No
• Minimum number of signal wires required	N/A	N/A	One flat pair	One pair	N/A	N/A
• Shielded cable required	N/A	N/A	Recommended	No	N/A	N/A
• Simple interconnect engineering	N/A	N/A	Yes	Yes	N/A	N/A
• Reduction of hard wire distance to the FCU for each FSCU	N/A	N/A	Bus topology	Bus topology	N/A	N/A
• Maximum signal cable length	N/A	N/A	Five to Seven miles	Seven miles	N/A	N/A
• Regeneration of control/status signals at each FSCU	N/A	N/A	No	No	N/A	N/A
❑ Radio interface available	No	No	Yes	Yes	No	No
FCU to FSCU Communication Link Software						
❑ Command and verify sequence on all FCU to FSCU communications	N/A	N/A	Yes	Yes	N/A	N/A
RSC Power						
❑ Phantom (signal line) power capability	No	No	No	No	No	No
❑ Solar power capability	No	Yes	Yes	No	No	No
❑ 110 to 125 Vac power capability	Yes	Yes	Yes	Yes	Yes	Yes
• Power line surge protection	Yes	Yes	Yes	Yes	Yes	Yes
RSC Miscellaneous Considerations						
❑ RSC clock accuracy	N/A, all clocking done at MCU	Clock refreshed by MCU	Information not available	Clock refreshed by MCU	Clock refreshed by MCU	Clock refreshed by MCU
❑ Battery backup for RSC clock / timing functions	N/A, all clocking done at MCU	Yes	Yes	Yes	Yes	Yes
• Battery backup duration	N/A	10 years	Two years	10 years	10 years	Six months
❑ Automatic daylight savings time clock correction	Yes, if supported by MCU computer	Yes	No, manual through central	Yes, if supported by MCU computer	Yes, if supported by MCU computer	Yes, if supported by MCU computer
❑ Enclosure lightning protection	Yes	Yes	Yes	Yes	Yes	Yes
❑ Stainless steel housing for all RSC electrical and electronics	Yes	Yes	Yes	Yes	Yes	Yes
❑ Easily accessible (from housing exterior) electrical connections	Yes, pigtail arrangement	Yes	Yes	Yes	Yes	Yes
• Barrier strip connections for stations	No	Yes	Yes	Yes	Yes	Barrier / Connector
• Barrier strip connections for signal	No	Yes	Yes	Yes	Yes	Barrier / Connector
❑ Foreign language option for command and display	No	Yes, Spanish at RSC only	Yes, Spanish, Hebrew & Italian	No, not at RSC	Yes, Spanish, Japanese & French	No, not at RSC

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3.5 Current "State-of-the-Art" at Caltrans

A considerable amount of expertise regarding the remote control of highway irrigation already exists within Caltrans. Many Caltrans landscape architects, engineers, and maintenance personnel possess valuable information that should be considered when making decisions concerning central control. A comprehensive assessment of their expertise in the field is presented here.

The presentation is divided into three sections, a survey of Caltrans RIC sites, a survey of Caltrans personnel involved in RIC projects, and a survey of an irrigation control program for the Model 170 controller. A standard questionnaire was developed for the personnel survey. A representative sample of Caltrans personnel in several districts were interviewed and several RIC sites were visited.

3.5.1 Caltrans RIC Sites

District 2

District 2 has installed a single Aquametrics Com-1 RSC located at State Route 299 and post mile 25. The RSC is controlling a total of six stations and uses the system's moisture sensing and flow monitoring features. Currently, a dial telephone CL is being installed to link the RSC with an IBM personal computer located at the Redding maintenance station. This will be used by the maintenance supervisor to monitor irrigation activities at the site. The RSC has been in use since the late summer of 1991.

Initial results are mixed. The maintenance supervisor, Mr. John Dobson, indicated that during the end of the 1991 summer it was necessary for the moisture sensing devices to be disabled. During the extremely hot weather, the sensors were indicating a "wet" soil condition when the vegetation was still in need of water. Mr. Dobson suspects that the sensors were located incorrectly by the manufacturer's representative and are not accurately reflecting the average soil moisture content of the irrigated area. He also indicated that further adjustment and optimization during an entire summer was necessary before finally evaluating the effectiveness of the system.

For more information contact: Ms. Vickie Bacon, District Landscape Architect, Redding, (916) 225-3476 and Mr. John Dobson, Highway Maintenance Supervisor, Redding, (916) 225-3518.

District 3

District 3 participated in a demonstration of the Motorola MIR 5000 system located at the I-5, State Route 99 and Business I-80, US-50 interchange (Oak park interchange). The MCU was located at the District 3 offices in Marysville. A total of four RSCs controlling approximately 16 stations each were located at the interchange. Flow monitoring was used in

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the trial. The system CL was implemented using trunked radio. The demonstration took place in 1991 and all equipment has since been removed.

The nature of the trial was to demonstrate the capabilities of the MIR 5000 system and the usefulness of a RIC system in general. The District Landscape Architect, Mr. Tom O'Donnell, feels that the demonstration was successful. In his opinion, RIC systems would aid water conservation efforts in District 3 and that the technology currently exists to implement such a system.

For more information contact: Mr. Tom O'Donnell, District Landscape Architect, Marysville, (916) 741-4436.

District 4

District 4 is currently participating in a demonstration of the Motorola MIR 5000 system located at the US-101 and State Route 12 interchange. The MCU is located at the Santa Rosa maintenance station. One RSC is controlling 36 stations and utilizing the system flow monitoring features. The system CL is implemented using trunked radio. The demonstration is being installed at the time of this report. As such, no information is yet available on the success of the trial.

For more information contact: Mr. Drago Dolar, Maintenance Superintendent II, Petaluma, (707) 762-6641 and Mr. Joe Johnson, Maintenance Supervisor, Santa Rosa, (707) 546-0644.

District 5

District 5 is currently engaged in a RIC system project that is scheduled to go out to bid in June 1992. The project is divided into two phases, both of which are located in Santa Barbara. Phase one is located along US-101 between Castillo street and the Junipero pedestrian crossing and phase two continues from the Junipero crossing to State Route 154. The irrigation of 33 acres will be under RIC system control. The MCU will be located at the Upper State street maintenance station with the maintenance supervisor as the primary operator. A total of nine RSCs (phase one and two combined) will be located at the field sites. Flow monitoring will be used to supervise irrigation from a 137 GPM reclaimed water source. The CL will be implemented using radio although the specific type (conventional, trunked or cellular telephone) has not yet been determined. A third project is currently in the design phase. It will extend RIC system control along US-101 from Castillo street south to Milpas street.

For more information contact: Mr. Dennis Reeves, Landscape Architect Project Manager, San Luis Obispo, (805) 549-3509 and Mr. Timothy Richards, Landscape Architect, San Luis Obispo, (805) 549-3627.

District 6

District 6 is currently engaged in a RIC system project that will place all highway landscape irrigation in the Fresno area (approximately 300 acres) under RIC system control.

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The contract has been awarded as of May 1992. The project is a retrofit of existing landscaped sites. The MCU will be located at the Railroad maintenance station in Fresno and will be operated by the district water manager. A total of 32 RSCs with 32 stations each and flow monitoring will be used in the field. The contractor is currently evaluating RIC system vendors for compliance with the project specifications. Early indications are that the contractor intends to install a Buckner COPS Universal system that has been enhanced to meet the project specifications. The enhancements include: data acquisition, irrigation program storage in the RSC, trunked radio CL support and CIMIS interface support.

For more information contact: Mr. Ronald Russak, District Landscape Architect, Fresno, (209) 488-4040, Ms. Kristin Layton, Water Manager, Fresno, (209) 488-4065 and Mr. L.R. Johnson, District Landscape Specialist, Fresno, (209) 488-4063.

District 7

District 7 is currently engaged in three RIC system projects, all are at different stages of completion. The first project is located at the I-710 and State Route 60 interchange and is under construction. The central control is implemented using a Rain Bird Maxicom system. The MCU is located at the Humphreys maintenance station and will be operated by the maintenance supervisor. A total of 13 RSCs (13 FCUs and 21 FSCUs) are installed in the field. The system CL is implemented using dial telephone. Both flow monitoring and environmental feedback with a single weather station are utilized. The project is a retrofit of an existing hydraulic design.

The second project is located at the I-710 and I-405 interchange. The bid was advertised on April 6, 1992 and is scheduled for opening May 14, 1992. The project involves 12 sites with a total of 21 RSCs. The system incorporates flow monitoring, however no environmental feedback will be used

The I-110 and I-405 interchange is also slated for RIC automation. This project is currently in the early design phase and the final hydraulic design as well as the number of site RSCs has not been established. The system will be controlled by the same MCU that is used for the I-710 and I-405 interchange project.

For more information regarding the first two projects contact: Ms. Suzanne Namba, Landscape Architect, Los Angeles, (213) 897-0635. For more information regarding the I-110 and I-405 interchange project contact: Mr. Gary Kato, Landscape Architect, Los Angeles, (213) 897-0619.

District 11

District 11 has installed three RIC systems and is planning to install a fourth in the fall of 1992. All the locations use the Motorola MIR 5000 system. The systems also utilize flow monitoring and pressure monitoring.

The Oceanside system has been operational since 1988 and was the first system installed in the district. The MCU is located at the Carlsbad maintenance station and is operated by the maintenance supervisor. A total of ten RSCs are located along a five mile section of I-5. Flow and pressure monitoring is used extensively to supervise irrigation from a single reclaimed water source. The system CL is implemented using trunked radio through an SMR.

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The Kearny Mesa system is located at the I-8 and I-15 interchange. A total of three RSCs control irrigation along 1.5 miles of highway. The MCU is located at the Kearny Mesa maintenance station and is operated by the maintenance supervisor. As with Oceanside, flow and pressure monitoring is used extensively to supervise irrigation from a single reclaimed water source. Trunked radio through an SMR is used for the system CL.

The third system in District 11 is located at Bostonia. A total of five RSCs are placed along a ten mile segment of I-8. The MCU is located at the Bostonia maintenance station and is operated by the maintenance supervisor. Both the flow and pressure monitoring features of the MIR 5000 are used. The site hydraulic systems are supplied with city water. The system CL is implemented using trunked radio through an SMR.

District 11 is currently engaged in a fourth RIC system project that is scheduled for completion by fall 1992. The project is located at Otay Mesa. Four RSCs located along a two mile section of I-5 will control the highway landscape irrigation system. One MCU will be located at the Otay Mesa maintenance station and will be operated by the maintenance supervisor. Trunked radio through an SMR will be used for the system CL. The project will use city water for irrigation.

The RIC systems installed in District 11 have proven to be very successful. The Oceanside system designer, Mr. Ray Traynor, indicated that the capability of precise flow management was the primary reason a RIC system was initially considered. The reclaimed water source had limitations on the total volume supplied, the maximum flow allowed and on the time of day it could be used. Additionally, the single gravity fed source was used for the entire five mile project, necessitating tight flow control in order to maintain acceptable pressures.

The maintenance supervisor charged with the operation of the Oceanside system, Mr. Tom Tuck, has also been pleased with its performance. He indicated that the system has resulted in a much more efficient use of personnel. Both the extensive use of remote irrigation programming and the use of equipment failure alarms are primarily responsible for the increased efficiency. He also indicated that the ability to quickly adjust irrigation in response to dramatic weather changes (high wind, rain, etc.) is very valuable. An additional advantage to the use of flow control is the reduction of fatigue to the site hydraulic systems. Mr. Tuck indicated that the repair of valves and the frequency of hydraulic equipment failure has been reduced. The flow history features of the MIR 5000 system has also proved useful in resolving disputes (over excessive use of water) with the reclaimed water supplier.

For more information contact: Mr. Tom Ham, District Landscape Architect, San Diego, (619) 688-6719, Mr. Ray Traynor, Landscape Architect, San Diego, (619) 688-6738, Mr. Tom Tuck, Maintenance Supervisor, Carlsbad, (619) 438-7419.

District 12

District 12 is currently engaged in the installation of a Valcon V-III system located along State Route 22, from Trask avenue to the Santa Ana river. The MCU is located at the Orange maintenance station and will be operated by the maintenance supervisor. A total of 21 RSCs with flow monitoring are installed in the field. The system CL is implemented using trunked radio.

Two additional projects are planned for completion this year. Both will expand the Valcon system along State Route 22. The first will centrally control the irrigation from Trask

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avenue to Newland street. The second expansion will extend from Newland street to 0.6 miles east of the State Route 22 and I-405 separation.

For more information contact: Mr. Phil Olivares, Landscape Architect, Santa Ana, (714) 724-2462, and Mr. Kevin Tong, Landscape Architect, Santa Ana, (714) 724-2463.

3.5.2 Caltrans Personnel Survey

During the spring of 1992 several Caltrans personnel who have been involved with RIC system design or implementation were interviewed. The interview group primarily consisted of landscape architects at the following districts: District 2, District 4, District 5, District 6, District 7, District 8, District 11 and District 12. Some maintenance supervisors who have had direct RIC experience were also interviewed.

A summary of the interview responses are presented here.

What is your current perception of the effectiveness (advantages and disadvantages) of central control?

The general response to this question was that the implementation of RIC systems by Caltrans would greatly enhance the agency's water conservation efforts. Specifically, the majority of respondents feel that the primary advantages are:

1) Quick adjustment of field irrigation programs to account for dramatic climatic changes, such as rain or high winds.

2) More efficient use of personnel by allowing remote access for routine reprogramming and by rapidly identifying equipment trouble locations.

3) An increase in safety, both to Caltrans maintenance personnel and to the motoring public, on busy urban interchanges. This would be realized through the excessive-flow alarm and automatic-shutdown features of a RIC system. Also, central control would require fewer routine field visits, thereby requiring less exposure of maintenance personnel to highway hazards.

4) An enhanced method of flow control, often necessary when a reclaimed water source has supply restrictions.

Some concerns and disadvantages regarding RIC system implementation were also expressed. These included:

1) Many of the RIC systems may have more capability (and complexity) than is needed. This added complexity may deter field maintenance personnel from taking an active role in using the systems in an efficient manner.

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2) Some areas may have an excessive number of microclimates. This would make the adjustment of irrigation programs to direct environmental feedback (such as ET) impractical.

3) The initial cost of implementing a RIC system is high. The California Transportation Commission (CTC) sets the amount of money that can be spent per acre on landscape. This creates many challenges for the RIC system designer when trying to utilize more advanced (and costly) features.

How would you envision a remote irrigation control (RIC) system being implemented in your district? Where do you feel the boundaries of each system should be located?

The response to this question was very similar for all of the District personnel interviewed. There are four main recommendations:

1) A standard RIC system should be selected for use district wide. This is necessary due to the complexity of most RIC systems and the frequency with which field personnel change work locations.

2) RIC system boundaries should coincide with the existing maintenance station areas of responsibility. The current system of landscape maintenance operations is effective and does not warrant significant change.

3) The MCU should be located at the associated maintenance station and the primary operator should be the maintenance supervisor. The respondents feel that the personnel who are most familiar with the landscape in a given area should have control of that area's irrigation.

4) A full-time "Water Manager" position should be implemented in each district with RIC systems. Some larger districts may require a position for each region. The water manager should have a master MCU for his area of responsibility. This MCU would have access to all of the associated maintenance station MCUs for oversight and coordination in periods of unusual events (natural disasters, etc.). The primary function of the position would be: to optimize RIC operations in order to enhance water conservation, to provide training for maintenance supervisors on the use of their RIC systems and to act as an irrigation knowledge resource for field personnel within their area of responsibility.

Should a RIC system be integrated into current Traffic Operations Centers?

The overwhelming response to this question was that RIC systems should not be integrated into a Traffic Operation Center. The respondents feel that the information needs of the two systems are radically different and integration would not be successful. The format of a TOC, with 24-hour monitoring, etc., would be unnecessary for a RIC system. Additionally, most respondents feel that landscape operations would not be given the appropriate attention.

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What RIC system features are important to your district? What kind of reports or field feedback would be valuable to you?

The response to this question had two major components. First, features that would be useful if the RIC system was implemented with or without a water manager position in the district. These include:

1) Flow monitoring with break detection and automatic valve shutdown. Additionally, flow history reporting to aid water conservation efforts.

2) The ability to download irrigation programs from a central location.

3) Flow control for reclaimed water applications.

4) Actuation of irrigation stations "on site" with a hand held radio.

5) Remote site equipment (valves, etc.) failure alarm.

6) Wind monitoring with high wind automatic shutdown.

7) Automatic rain detection and shutdown.

Second, features that would be useful, but would involve a more detailed understanding of irrigation theory. The implementation of these features would need a higher level of expertise, such as that held by a water manager.

1) Environmental feedback for adjusting irrigation programs.

2) Individual station control for adjusting irrigation factors (slope, exposure, etc.).

3) Infiltration rate compensation.

4) Moisture sensing.

Do you feel that the needs of your district are unique enough to warrant the development of a custom RIC interface?

The response to this question was mixed. The majority of respondents feel that none of the currently available RIC systems are ideal for highway irrigation. The majority also feel that after Caltrans has gained some experience using commercially available systems, development of a custom system would be advantageous. The major areas identified for improvement are:

1) The user interface. A more natural (user friendly) interface should be developed. More use of icons and graphics should be explored.

2) A more global or "system wide" approach to the MCU software should be developed. This should include a map based status and alarm display.

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3) Standardization of systems. This should be perused so that related long and short term issues can be addressed. These include: the availability of parts, system installation and operation expertise, and the availability of trained repair personnel

It should be noted that two of the respondents were extremely skeptical of the ability of Caltrans to develop a system. Because of this, they feel that a custom system should not be pursued.

Where do you see highway irrigation going in the next 5 to 10 years? What are the long range trends?

All of the respondents feel that water conservation in highway irrigation is essential in the coming years. Several parallel approaches, including RIC system implementation where applicable, will be used to achieve water savings. Water-sensitive designs with basin watering, increased use of mulch, use of drought tolerant plants and the discontinued use of ground cover, will aid in conservation. In applicable areas, projects will be designed so that irrigation is used to establish vegetation and then discontinued. In older urban areas the effort to automate existing manual systems will continue. Some of these upgrades will be candidates for RIC implementation.

The increased use of reclaimed water will also have a substantial impact on highway irrigation. In urban and suburban areas, cities are now developing reclaimed water master plans. As these plans are implemented in the next 10 to 20 years, reclaimed water sources along the highway will become commonplace.

Do you foresee any problems implementing a RIC system in your district or state wide?

There are two primary concerns that respondents have with regard to implementing RIC systems. The concerns are:

1) That adequate training and staffing will not be provided. Most feel that the proper implementation of a system will be a very time consuming process in order to achieve water conservation.

2) That the level of funding set by the CTC will be inadequate for a proper RIC installation. This may not allow the irrigation system designer to take full advantage of the system capabilities.

3.5.3 Model 170 Irrigation Control Program

The Model 170 Irrigation Control Program has been developed by Caltrans District 4 for highway irrigation applications. The Model 170 is a Caltrans traffic signal controller. In this application it is used as a RIC system Remote Site Controller (RSC). The intent of the project is to take advantage of the availability of many spare Model 170s. The Model 170 Irrigation Control Program features time based programming and distributed intelligence.

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General System Overview

The Main Control Unit (MCU) is implemented on an IBM PC. Currently, this program does not include centralized control; it only allows programming through an RS-232 interface. There is no support for weather stations or any other environmental feedback.

The RSCs are capable of stand alone operation and can be programmed locally. Up to 24 stations can be controlled by each RSC. Currently, there is no support for data acquisition. The RSC's user interface features LED displays, indicator lights, and a hexadecimal keypad. Local programming is performed by entering commands encoded as hexadecimal numbers with the keypad.

MCU Software

The Model 170 Irrigation Control Program software user interface is menu driven and does not provide support for mouse or graphics.

Irrigation programs are called records and specify a time based program for a single RSC. The 24 stations in an RSC are divided into 3 watering zones having 8 stations each. Up to 4 ON/OFF times can be defined for each station. The irrigation cycle length is 7 days and each station may have independent watering days.

The Model 170 Irrigation Control Program provides a very simple environment for time based irrigation programming. This program has been developed with a limited budget. Many Model 170s are available from District 4 for a nominal fee. In addition, considerable maintenance expertise and spare parts are available. Upcoming improvements include dial telephone communications and data acquisition capabilities.

3.5.4 Caltrans Personnel Reference

Following is a list of RIC-related Caltrans personnel.

Headquarters

Dennis Cadd
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Transportation Facilities Enhancement Office
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Dan Johnson
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Maintenance Superintendent II
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George Juilly
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CHAPTER 4

FUTURE TRENDS OF REMOTE IRRIGATION CONTROL SYSTEMS

4.1 Remote Site Equipment Future Trends

The future trends in remote site equipment indicate support of the general trend toward increased utilization of environmental feedback to implement emerging irrigation paradigms and to provide tighter control of the hydraulic system. This will be implemented by use of more sensing equipment and more powerful data acquisition systems. As an example of new sensing equipment, the ETgage is presented as an emerging alternative to weather stations and CIMIS for ET driven irrigation scheduling.

4.1.1 Remote Site Controller

Future remote site controller (RSC) design trends are generally characterized by increased local intelligence and improved user interfaces. The continuing decrease in the price of memory and microprocessor chips, coupled with new and affordable front-panel keypads and larger LCD displays, make it possible to implement more user friendly designs and to augment the RSC's decision-making abilities. The emerging use of high level programming languages for firmware implementation and the availability of sophisticated embedded-system development tools will result in shorter development cycles and enable a more ambitious set of features to be implemented cost effectively. The increase in RSC computational power, together with advances in sensing devices, will enable sophisticated data acquisition designs to add the necessary feedback for highly automated operation. As a result, the RSCs will provide further automation of irrigation tasks and advanced water management support without imposing excessive workloads on the Main Control Unit (MCU) and the Communication Link (CL). A wider variety of CL technologies will be supported, extending the range of typical area coverage.

Cumbersome user interfaces requiring memorization of complex keypresses and utilizing small displays are now being replaced by single-function-per-key designs with menus and on-line help. Simple-to-operate designs will become more prevalent. Also, there is a trend to make the RSC user interface as similar as possible to the MCU interface in terms of organization, nomenclature and display. This will result in faster learning curves for maintenance personnel since they will need to learn only one unified and consistent interface.

Concerning future trends in irrigation features, RSCs will provide local support for a wider variety of irrigation programming paradigms based on environmental feedback. Volume based programming, precipitation based programming (i.e., specifying water delivery in inches), ET driven irrigation, infiltration rate compensation, and moisture sensing are a few examples of the new features that will eventually become as commonplace as time based programming is today. The common goal of these sophisticated techniques is to optimize irrigation for water conservation purposes.

Flow monitoring and flow optimization will also become more popular, improving hydraulic system performance and resulting in reduced maintenance requirements. The ability

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to respond to unusual climactic conditions and faults in the hydraulic system will also help water conservation efforts.

4.1.2 The ETgage

The ETgage is an instrument that measures reference evapotranspiration directly. Its low cost could make it an attractive alternative to weather stations in applications with high climatic variability among sites.

The ETgage is basically a digital atmometer with a communications interface. Atmometers have been used since the turn of the century to study plant transpiration. In 1985 Jon Altenhofen of the Northern Colorado Water Conservancy developed a field instrument version to measure alfalfa reference evapotranspiration [50]. This modified atmometer consists of a cylindrical water reservoir with a ceramic cup mounted on top of it. The ceramic cup, also known as a Bellani cup, is covered with a rough green canvas to simulate plant solar radiation absorption and leaf diffusion resistance to evaporation. Distilled water is added periodically during operation and a graduated sight plastic tube is provided to read the instrument's water level. The amount of water evaporated from the atmometer is used as an indication of alfalfa reference evapotranspiration.

Broner and Law [51] have evaluated the use of the modified atmometer for estimating reference ET. Their conclusions indicate there is satisfactory agreement between atmometer readings and Penman equation results obtained from weather station data (the percent differences between the two range from 0% to 17.2%).

The ETgage adds a digital interface to the modified atmometer; interfaces to data-loggers, Remote Terminal Units (SCADA controllers) and IBM PCs are available. The ETgage's circuitry sends a pulse whenever the water level drops by 100th of an inch, an output similar to that of a tipping bucket rain gauge. The data acquisition software is generally responsible for accumulating the pulses and providing the ET readings, except the IBM PC interface, which already provides accumulated ET readings. Also, a remote LCD display may be hard wired to the ETgage to minimize errors resulting from taking visual readings off the sight glass tube.

The manufacturer of the ETgage, C&M Meteorological Supply, P.O. Box 5723, Riverside, CA, 92517, (714) 780-7691, claims a 3.7% discrepancy against cumulative CIMIS ET readings taken over a recent 5 month trial period. The ETgage is priced at $850.00 in quantities of 5 or more. In comparison, weather station prices start at $4,000 and weather station software is priced at approximately $2,500. Maintenance requirements include refilling the gauge with distilled water every two months (may vary slightly), and cleaning the ceramic cup annually. It should be noted that freezing is a problem as it can destroy the ceramic cup. The unit must be removed during the winter months in areas where the temperature is expected to reach below freezing. The simplicity and low cost of the ETgage relative to weather stations could make it practical to use several units in systems with many different microclimates. This would allow better environmental sampling in order to implement ET driven irrigation scheduling.

Another digital atmometer is currently available from a different vendor. This device is called ETNow and is manufactured by Automata, 16216 Brooks Road, Grass Valley, CA, 95945-8816, (916) 273-0380.

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4.2 Communication Link Emerging Technologies

The decade of the 1980s was truly a revolutionary period for remote data acquisition and control systems. As stated earlier, the advent of small, powerful and inexpensive microprocessors and memory cleared the way for systems with distributed decision-making abilities. While the impact of this has been seen in the Remote Irrigation Control (RIC) equipment itself, it has also greatly impacted the communications networks that are now available to industry and the public. Phenomena such as the cellular telephone network, trunked radio systems and digital telephone systems are all the result of being able to spread the processing power necessary to perform complicated supervision tasks to many geographic locations. In many cases, the ideas that form the basis for today's systems were conceived 40 or 50 years ago. However, the ideas were not practical until inexpensive distributed intelligence allowed the extremely numerous decisions to be placed in a localized hierarchical format.

The decade of the 1990s will see a continuation of this trend. Providing more mobile access to a communications network that can accommodate both data and voice. This accessibility will have a significant impact on RIC systems by removing the difficulty associated with choosing a proper CL. Often, in current system designs, the type of Communication Link that is needed to support access to a given site is an overriding factor in the choice of a system. This will be much less of a problem in years to come as the mobile data network is developed.

Several emerging Communication Link technologies are presented in the following sections. Some of the technologies discussed are ideal for the requirements of a RIC system. Others could be used with the qualifications that are explained in the text. It is useful to remember the basic requirements of RIC communications: a relatively small amount of data is transferred so high data rates are not necessary, quasireal-time access is preferred so that desired actions can be executed rapidly, and radio connectivity is often desired so that installations can be made quickly with a minimum of expense.

4.2.1 Packet Radio

Packet radio is an exciting emerging technology that is perfect for exploitation in RIC applications. Data that are to be transferred are divided up into segments called "packets." Each packet is a stand-alone unit from a transmission standpoint. It contains a segment of data, the ordering information for that data (how the segment fits into the total message), all the routing information necessary to be transported from source to destination, error correction information, and supervisory information. Once the packet is transmitted, it is repeated by other transceivers on the network until the destination is reached. The advantage that this technology provides is that sites that act as field control points can also be used as "store and forward" repeaters for the rest of the network.

This type of system lends itself very well to highway RIC applications. RSCs placed along the highway right-of-way can act as the network repeaters. The linear nature of the highway allows the repeaters to be located every few miles. Very large RIC systems can be accommodated in this way without the need for a mountaintop repeater at a central location. In

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addition, the interference problems associated with conventional radio are minimized since each site only needs to communicate with the next location in the "chain."

Although packet radio has been in existence since the early 1970s [64], wide application of the technology has only occurred in the last ten years. Currently, there are many geographically diverse packet radio telemetry systems in operation. Weather Network, Inc. (Chico, CA) has implemented a weather data collection system with sites located throughout northern California. The entire system uses packet radio to communicate with the field weather stations.

In addition to private networks, commercial packet radio networks are available. ARDIS, a Motorola and IBM joint venture, and RAM Mobile data both have systems in place that utilize this technology [65]. Typically, a user would pay a "per message unit" charge as well as a monthly connection fee. These systems are currently limited to coverage in urban areas of the state.

4.2.2 Satellite Radio

Satellite radio communication has become commonplace in the last decade. Everything from television programming to data is now delivered via satellite. Classically, satellite delivery systems are considered a broadcast type of delivery system, i.e., a single source of information or programming is delivered to many receive sites. No return communication is available. In fact, the Network Services Control RIC system, discussed in the surveys, uses a satellite delivery system to transmit control information to its RSCs. Note that the communication in this system is broadcast-like, the irrigator can only adjust the water budget and has no way of obtaining site feedback.

Important developments in using satellite radio for bidirectional communication are currently underway. The Mobile Satellite Service (MSS) and the Iridium project look promising for use in SCADA applications.

MSS is designed to provide a mobile telephone system to users who are outside the range of a standard terrestrial cellular telephone system. The MSS satellite, called MSAT, is designed for a geosynchronous orbit and is scheduled for launch in 1994 [66]. It operates on the L-band of frequencies (near 1600 MHz) and, as such, only requires a very small antenna. Expected coverage includes all of North America [66]. The site equipment costs are expected to be similar to that of trunked radio. Subscribing to the service will involve a service connection fee, a monthly subscription fee, and a per-minute usage fee. The rates are expected to be competitive with cellular telephone "roaming" rates [67].

The Iridium project is a far-reaching proposal that has been undertaken by the Motorola Corporation. It is designed to provide a world-wide cellular telephone network using a constellation of low-earth orbit satellites. The scheduled date of operation is late 1996. As with MSS, Iridium communication takes place on L-band. The cost of the service will be high when compared to conventional cellular telephone (three to ten times that of cellular) [68]. But, because the satellites are in low-earth polar orbits, there is less transmission delay and service is a better approximation of standard dial telephone service.

Both of the technologies may eventually prove very useful for RIC applications. There are many advantages to using this type of a system. Since the communications with the satellites take place on L-band, the antenna required is very small (roughly the size of a grapefruit). This lends itself to RIC applications where larger antennas would become a target

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for vandalism. The site equipment is fairly inexpensive when compared to terrestrial based radio technologies. RSCs can be installed, connected to the RIC network and operational within a very short period of time. This is a very important advantage since it minimizes the effort needed to engineer the system Communication Link.

American Mobile Satellite Corporation (AMSC), the company launching MSAT, has recognized the potential market for industrial SCADA applications. This may prove to be advantageous for RIC applications, since site equipment that is designed specifically for data acquisition and control is already planned [67].

The primary disadvantage to this technology is the ongoing costs associated with using the network. Initially, the cost of service may make implementation of this technology in a RIC CL prohibitive. However, as was demonstrated with terrestrial cellular telephone, the cost of service should decline as the popularity of the service increases.

Another satellite radio technology that may have limited applications in RIC is a Very Small Aperture Terminal (VSAT) network. This technology has been used by many companies with large, geographically diverse data networks to avoid using private line telephone data transmission channels. The name VSAT comes from the type of earth station used at each remote site (a parabolic reflector with a diameter of less than 1.8 meters) [7]. Each earthstation communicates with the network hub earthstation through a geosynchronous satellite. The hub provides the supervision and control over the network. Since the equipment associated with the hub earthstation is extremely expensive, independent companies have developed services which allow multiple VSAT networks to use the same hub (shared-hub networks). These services allow smaller networks to use VSAT technology without the expense of dedicated hub facilities.

Industries with important SCADA applications, such as monitoring a pipeline for the transmission of natural gas, have used VSAT networks to control pumping stations [46]. Generally, VSAT networks provide excessive capacity for individual RSC access in RIC applications. However, if RIC data are multiplexed with other Caltrans telemetry needs, such as ramp metering or traffic signal control data, a VSAT network may prove very useful.

4.2.3 FM Radio, Broadcast TV and MDS Media Sharing

For many years, FM radio broadcasters have made excess capacity within the FM broadcast channel available to industry and other groups. The most common example of the use of this technology is the commercial-free background music in many large department stores. The service, called FM Subsidiary Communications Services (SCS), may be used for a wide variety of applications [69]. Data as well as voice can be transmitted over these broadcast sub-channels.

Equipment is added to the FM broadcast transmitter to inject a subcarrier above the program audio. The process is a form of Frequency Division Multiplexing (FDM). The subcarrier is only detectable with a special receiver that is able to isolate the signal. This technology provides a way to establish an inexpensive control network that utilizes existing transmission facilities.

Another technology that is readily implemented and uses existing transmission facilities is Vertical Blanking Interval (VBI) data transmission. This type of system uses the excess capacity within a television signal to transmit control data to remote sites. It has been used successfully for load control in power distribution systems. Equipment is added to the

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television transmitter to multiplex data onto the video signal during the vertical blanking interval. At the remote sites, special decoders are used to strip the data from the received signal.

There are primarily two television services that may implement VBI data delivery, standard Broadcast Television and the Multipoint Distribution Service (MDS, also called "wireless cable") [70].

Both FM SCS and VBI data are readily exploitable for use in Remote Irrigation Control systems. The primary advantages in using these types of systems are: the technology is relatively inexpensive, the coverage of the transmitted signal on which the data is multiplexed is well known, the receive site antennas are small and inexpensive (a standard FM or TV antenna), no direct licensing is required, the system can be implemented in urban areas where licensing new radio frequencies is difficult. The major disadvantage to using this type of a system is that it is unidirectional, i.e., data acquisition and alarm functions at the RSCs could not be supported.

4.2.4 Telephone Digital Services

The current trend in telephone data communication is to provide a completely digital transmission system. This type of system has many advantages over traditional analog circuits. Regeneration of signals at intermediate points that eliminates cumulative noise, the ability to test circuits remotely, and the ability to reconfigure circuits remotely all contribute to an increase in reliability over analog systems. The conversion of inter-office telephone facilities to digital has been underway for many years. However, the conversion of the local loop (the cable from the Central Office to the subscriber) is still a major problem in most areas. In the years to come, the total conversion of the network will eventually take place throughout the state. Currently, there are two telephone services, Advanced Digital Network (ADN) and Integrated Services Digital Network (ISDN), that offer entirely digital circuits and are practical for RIC applications in certain cases.

ADN is a entirely digital service that was intended to replace private line telephone data transmission channels. It is offered at a variety of different synchronous data rates from 2400 bps to 56 Kbps. The available circuit topologies are dedicated and very similar to private line services. Service availability is currently limited to the urban areas of the state [71].

ISDN is also an entirely digital network, but connections to different sites are switched. The service is being touted as the "dial telephone service of the future." The ISDN plan is to "offer consolidation of communication circuits with improved performance for voice, data and packet service connections between users" [14]. The service offers a variety of different data rates; however, the basic-rate service offers two 64-Kbps voice or data channels and one 16-Kbps channel. Currently, access to service is very limited and widespread use will most likely not occur before the beginning of the next decade [72].

For RIC application, both services provide excessive capacity. As with VSAT, if RIC data are multiplexed with other Caltrans telemetry needs, the use of these technologies may prove beneficial. The all-digital network does provide a much more reliable transmission system when compared to other types of CLs. If the ISDN network service costs decrease and availability increases (as is predicted), this type of CL may be very competitive even with the over capacity.

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4.2.5 Fiber Optics

The use of fiber optics for data transmission has become commonplace within this decade. The entire long-distance telephone network is being converted to fiber-optic facilities. This type of transmission offers extremely high capacity and has many advantages over metallic conductors. The advantages include: improved bandwidth, distance, noise immunity, security, safety, and mechanical characteristics [73]. Fiber-optic systems modulate light with the digital information to be transmitted. The light signal is then directed to the destination over a non-conducting waveguide (an optical fiber). At the receiving end, the modulated light is then converted back into digital electrical signals.

Fiber optics has been used in various SCADA applications. Pacific Gas and Electric has implemented a power network monitoring system using fiber optics in downtown San Francisco [34]. For RIC applications, these systems are currently cost prohibitive due to the expense of the cable and equipment. However, in the future, fiber optic cable in the field will become commonplace for other network control needs (power utility, telephone, cable TV, etc.). At that time, use of the excess capacity for a RIC system CL may be very attractive.

One possible way of taking advantage of the capacity of a fiber-optic system is to combine it with another promising technology, packet radio. In this scenario, the fiber-optic system would be used as the "backbone" of a large RIC system. The backbone could be installed along a major highway or other linear structure. As an example, the State Department of Water Resources has installed a fiber optic cable along the State Water Project canal for telemetry use [72]. At locations where there is a concentration of RSCs, a packet radio node could be established to make the final CL connection with the fiber. This would allow the best features of both technologies to be utilized, the capacity of fiber optics and the geographical flexibility of packet radio. This same type of system could also be used for other Caltrans telemetry needs.

4.2.6 Implementation of RIC with the Public Safety Microwave System

The Public Safety Microwave system is an impressive network designed to provide radio communications to Caltrans and California Highway Patrol (CHP) vehicles. The system is comprised of microwave links that connect mountaintop repeater sites with various dispatch centers. The network quite literally has "multiple -hop" radio backbone paths that traverse the entire State. Use of the system for highway telemetry would be a natural extension of its current function.

The system is designed to provide mobile radio coverage of highways within the State. This means that the mountaintop sites are already developed, radio coverage patterns are already well known, and a microwave system is in place to transport the data received at the transceiver sites to lowland dispatch centers. The system was installed and is maintained by the Department of General Services, Telecommunications Division. According to Jim Kirstein, Head of the Microwave Planning and Design Unit, (916) 657-6130, there is excess capacity available on the system for telemetry use. In addition, Caltrans is in the process of converting the mobile radios used in maintenance vehicles from 47 MHz to a new 800 MHz system. The abandoned 47 MHz frequencies may be usable for a packet radio type of telemetry system after the conversion is complete [17]. The development of such a system would greatly enhance RIC system implementation by simplifying the establishment of communication with the RSCs.

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4.3 Main Control Unit Future Trends

This section presents the future trends in Main Control Unit (MCU) design for Remote Irrigation Control (RIC) systems. These trends fall into three categories: global system design, Communication Link (CL) support, and user interfaces.

4.3.1 Global System Design

The global system design trend concerns MCU software features that support the management of increasingly larger irrigation systems. Many current systems simply provide a means of bridging the distance from the operator to a single controller at a time. More recent RIC designs implement system wide features such as group programming, area status monitoring, and improved reporting capabilities.

Group programming enables classification of Remote Site Controllers (RSCs) and stations according to geographical location, watering requirements, vegetation, etc., for irrigation programming. This feature enables the system operator to have global views of the system during the process of programming irrigation, also allowing for quick programming changes to be made in special situations.

Area status monitoring reduces the complexity of monitoring a large system by furnishing multiple views of the system, each providing a different amount of detail ranging from the system level to the station level. In a typical application, the operator can initially choose the system view for status monitoring and then "zoom in" quickly to areas reporting alarm conditions, continuing to the controller level and possibly down to the problem station. This ability speeds the response time of maintenance crews and has the potential, for example, to save water in case of mainline breaks or broken laterals.

Custom reporting capabilities are necessary to support water management, maintenance work requests and other managerial functions. The data provided by these reports can be analyzed by other software to perform costs analyses and fine tuning of the system based on historical data.

4.3.2 Communication Link Support

In the communications area there is a trend for the MCU to support a wider variety of Communication Links (CLs). RIC system designers are becoming cognizant of the fact that no single CL can adequately serve all applications. This necessitates the support of mixed CL designs.

Currently, trunked radio and cellular telephone are gaining popularity in RIC system designs, clearly showing a move toward wireless CL technology. The growing mobile data communications market will soon provide a plethora of inexpensive wireless data networks that can be used as RIC CLs.

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4.3.3 Graphical User Interfaces

Most current MCU software is implemented as DOS character mode applications. The general trend in software design toward graphical user interfaces (GUIs) will also extend to MCU software design. As an example, Macintosh, Windows, and OS2 based MCU designs are beginning to appear in the market and are expected to become increasingly popular. The use of GUIs simplifies the training of system operators, increases productivity and provides support for data exchange with other applications. On the other hand, these advantages come at the expense of greater computing power requirements, more difficult software programming environments, and somewhat slower response times. The continuing decline in hardware prices will make the computing power required by GUIs affordable and provide acceptable response times for real time applications.

4.3.4 Mapping Software

Related to the use of GUIs is the trend towards the use of maps for system representation. This technology has been used, for example, in Supervisory Control and Data Acquisition (SCADA) systems to reduce the time needed to respond to situations demanding operator intervention [43]. The need to present information in a geographical context has spurred the development of off-the-shelf mapping software that can be integrated into custom software designs. Mapping software is expensive (on the order of $5,000 to $10,000) and requires high permanent storage capacity devices (such as CD-ROMs) to store the maps.

For RIC systems, maps can be used to indicate both site and controller locations graphically, thus eliminating the need of the operator to keep a mental picture relating controller names to their locations. As an example, Thompson's Mark-1 provides the ability to incorporate "as-builts" for this purpose. A further extension of this idea is to display status icons against a map background for system status monitoring and for controller addressing. In this manner the operator can "zoom in" to different view levels and access controllers more easily for programming, manual operation or status monitoring. This feature is not present in current MCU designs. Other applications include the presentation of report data in geographical form; for example, water consumption or number of alarms per site can be displayed against a district map.

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CHAPTER 5

CONCLUSIONS

The primary research objective of providing a comprehensive reference source for Remote Irrigation Control (RIC) systems has been satisfied by this report. A generic system model and set of benchmark features were developed to facilitate system comparison. A through study of currently available RIC systems was performed and presented. A detailed analysis of the communication methods used by currently available RIC systems was performed and presented. A survey of RIC expertise and information already existent within Caltrans was provided. Future technological trends regarding centralized irrigation control were examined and discussed. Lastly, a brief field guide booklet was produced for use as an abridged reference.

The following conclusions are based on the information gathered for the RIC system reference source.

1) The use of RIC systems for highway right-of-way irrigation is feasible. In some applications, such as when limited source reclaimed water is used, it is the only option available to meet constraints on flow, total volume, time of day, etc.

2) The diversity of Caltrans district needs makes the support of multiple types of Communication Links (CLs) a necessity. The proper choice of a CL transmission method is critical to the successful implementation of RIC.

3) The large geographic areas that may be covered by Caltrans RIC systems necessitate the use of distributed intelligence in overall system design. The individual Remote Site Controllers (RSCs) must be able to operate as independent controllers during periods of CL failure.

4) Generic data acquisition support is an important RIC system feature. It allows flexibility in the use of both current and future sources of environmental and operational feedback.

5) The ability of the RIC system to respond expediently to situations when irrigation should be suspended is important. This feature minimizes the hazard to the public and possible loss of property from abnormal events, such as excessive flow.

6) It is desirable to reflect the current Caltrans maintenance hierarchy when deciding the area covered by individual RIC systems. System control should be at the maintenance supervisor level.

7) A district (or regional) water manager position should be developed to provide guidance and assistance to Caltrans maintenance supervisors in RIC system operation and water conservation methods.

8) A RIC system specifically designed for highway right-of-way applications should be developed by Caltrans. The system should utilize emerging technologies in communication, data acquisition and control and environmental feedback. Development of a custom system should yield benefits in several

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areas such as: economies of scale in the per system implementation cost, system repair, maintenance personnel training and irrigation efficiency.

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CHAPTER 6

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CHAPTER 7

GLOSSARY OF TERMS

- AASHTO: see American Association of State Highway and Transportation Officials.
- ADN: Advanced Digital Network.
- Advanced Mobile Phone Service: the cellular telephone system implemented in the USA.
- Alarm paging: refers to the ability of the system to page selected operators when alarm conditions arise.
- Alarm response definition: enables the user to select predefined actions or to program custom responses to alarm conditions detected by the system.
- All call: refers to the ability of the system to address all remote site controllers (RSCs) simultaneously to issue global commands such as shutdowns.
- American Association of State Highway and Transportation Officials: the frequency coordinating agency for the Highway Maintenance service for bands below 800 Mhz.
- AMPS: see Advanced Mobile Phone Service.
- Analog communications: a communication method using transmission signals that have continuously varying values.
- Analog variable: a variable having a continuous range of values, e.g., the temperature measured with a mercury thermometer.
- APCO: see Associated Public Safety Communications Officers.
- ARDIS: Advanced Radio Data Information Service.
- Associated Public Safety Communications Officers: the frequency coordinating agency for the Highway Maintenance Service for the 800 Mhz bands.
- Asynchronous transmission: a data transmission scheme that frames characters to synchronize the independent clocks at both ends.
- Boolean variable: a variable having only two values, e.g., the state of a switch: open or closed.
- California Irrigation Management Information System: a public state-wide evapotranspiration data-acquisition system operated by the California Department of Water Resources.
- Channel bandwidth: the range of frequencies that can be transmitted with integrity over a given communication channel.

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- CIMIS: See California Irrigation Management Information System.
- CL: See Communication Link.
- CD-ROM: Compact Disc Read-Only Memory, a large-capacity optical storage device.
- Cellular telephone: A mobile telephone service transmission method using multiple radio frequency channels to allocate trunks to communicate through the Public Switched Telephone Network.
- Central Site Controller: the control and supervisory component of the Motorola Smartnet trunked radio system.
- Central Office: the part of the Telephone Network closest to the subscriber's premises. For dial telephone, this is where the first stage of switching takes place.
- CO: see Central Office.
- Co-channel interference: interference present in radio systems from other users of the same frequency.
- Conventional radio: A Communication Link using dedicated radio frequency channels.
- Communication Link: The component of a remote irrigation control system responsible for reliable transmission of data between two points, chiefly between the central point of control and the irrigation sites.
- CSC: see Central Site Controller.
- Data acquisition and monitoring: refers to the ability of the system to gather and monitor data from different types of sensors such as flowmeters, rain gages, etc.
- Data export support: means that data gathered by the system's Main Control Unit software can be ported to third party software such as spreadsheets, databases, etc.
- Dial telephone: a transmission method implemented using the Public Switched Telephone Network (PSTN) where transmissions require dialing a telephone number.
- Digital communications: a communication method using transmission signals that have only discrete values, e. g., telegraph communications.
- Digital variable: a variable having only discrete values, e.g., the day of the week.
- Distributed intelligence: indicates that the system's remote site controllers (RSCs) are capable of autonomous execution of irrigation programs downloaded from the Main Control Unit (MCU). In this manner contact with the MCU is not necessary after program download.

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- DTMF: See dual tone multifrequency.
- Dual tone multifrequency: a signaling method used by Touch Tone telephones to encode which key has been pressed with a pair of frequency tones.
- Environmental adjustment factors: factors, usually percent multipliers, that model environmental variables such as shading, slope, vegetation type, and others; and used to characterize the water demands of the remote stations with respect to an idealized site such as a weather station location.
- ET driven irrigation: means that evapotranspiration data are used by the system to determine water delivery requirements.
- ET driven system: one in which the amount of water to be delivered is adjusted as a function of evapotranspiration rate measurements.
- ETo: reference evapotranspiration.
- Evapotranspiration rate: a measure of the rate at which water is removed from the soil due to evaporation and plant transpiration.
- FCC: see Federal Communications Commission.
- FDM: see Frequency-Division Multiplexing.
- FDX: see Full-Duplex system.
- FEC: see Forward Error Correction.
- Federal Communications Commission: the federal regulatory agency in charge of licensing the use of the electromagnetic spectrum for communications.
- Filter and fertilizer programming: means that the system software explicitly supports programming the operation of such equipment (as opposed to using dummy stations for the same purpose).
- Flow optimization: means that the system is able to automatically rearrange the sequence of irrigation to maintain an even operating target flow, thus avoiding damaging pressure transients in the water delivery system.
- Foreign language support: means that the MCU or RSC user interfaces are available in a foreign language. This is important in California, where more than half of all irrigators in landscape and agriculture speak Spanish.
- Forward Error Correction: an error correction scheme where data are encoded to enable the receiver to detect and correct errors without retransmission.
- Frequency coordination: the part of the FCC licensing process where special agencies select frequencies for radio service applicants in order to avoid interference.
- Frequency-Division Multiplexing: a multiplexing method in which use of the communication line is allotted in frequency bands.

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- Full-Duplex system: a system in which simultaneous transmissions in both directions are possible.

- Geosynchronous orbit: an orbit 19,320 nautical miles above the equator. The period of this orbit is equal to the earth's rotational period. Consequently, communications satellites in this orbit appear to be stationary from the earth.

- Graphical User Interface: refers to the use of icons and pointing devices to interact with software. For RIC systems GUIs are used for the MCU software.

- GUI: see Graphical User Interface.

- Half-Duplex system: a system in which transmission is possible in both directions but only one way at a time.

- Hard wire: a Communication Link using metallic wires as transmission media.

- HDX: see Half-Duplex system.

- Infiltration rate compensation: refers to the ability of the system to divide the application of the target amount of water delivery so as to avoid runoff.

- Integrated weather station support: means that weather station data can be automatically monitored and used by the system for irrigation scheduling, as opposed to using third party software to gather the data and then entering it into the RIC system.

- Inter Exchange Carrier: a long distance telephone company.

- Irrigation cycle: the specification of the time interval after which the irrigation schedule is to be repeated, i.e., weekly, monthly, etc.

- Irrigation program: the specification of an irrigation schedule and the event driven adjustments associated with it. An example of event driven adjustment might be to stop irrigation when a pipe leak is detected.

- Irrigation schedule: the specification of station "on times" over a certain length of time, e.g., thirty minutes starting at 10 A.M. on Mondays and Wednesdays.

- ISDN: Integrated Services Digital Network.

- IXC: see Inter Exchange Carrier.

- LATA: see Local Access and Transport Area.

- LEC: see Local Exchange Carrier.

- Local Access and Transport Area: a division of the telephone network within which calls are provided by a local telephone company and therefore are not considered long-distance .

- Local Exchange Carrier: a local telephone company.

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- Local loop: the hard wire connection between a telephone subscriber and the Central Office.
- LOS: line of sight.
- Main Control Unit: the central component of a remote irrigation control (RIC) system where control and supervisory commands are issued to the field units.
- MCU: Main Control Unit.
- MDS: Multipoint Distribution Service.
- Message trunking: a trunked-radio channel assignment scheme where channels are assigned for the duration of a session or conversation.
- Mobile Telephone Switching Office: the office providing cellular telephone subscribers switching and access to the PSTN.
- Modem: Modulator-Demodulator, a communications device used to send information by varying (modulating) the amplitude, phase, or frequency of an analog sinusoidal carrier and also capable of receiving information in that form.
- Moisture sensing: refers to the explicit built-in support of moisture sensors to regulate irrigation.
- MSS: Mobile Satellite Service.
- MTSO: see Mobile Telephone Switching Office.
- Multiple Access: a control protocol where communications may be initiated by any device in the network.
- Multiplexing: a method by which multiple messages (from different sources) are transmitted over the same communication line.
- Multitasking: refers to the ability of the MCU to run multiple programs simultaneously. This allows the operator to perform other tasks such as word processing or data manipulation while the RIC system functions are performed in the background.
- NABER: see National Association of Business and Educational Radio.
- National Association of Business and Educational Radio: the frequency coordinating agency for the business radio service.
- Password protection: refers to the ability of the system to require passwords from users when the MCU software or the RSCs are accessed.
- Polar orbit: a low-altitude orbit over the earth's poles used to provide satellite coverage over several land masses.
- Polling: a control protocol where all communications are initiated by a master device (i.e., the MCU).

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- Precipitation based system: one in which the amount of water to be delivered is expressed in terms of volume per unit area, in the same manner that rainfall precipitation is expressed. Usually expressed in terms of inches or millimeters.
- Private line telephone: a Communication Link that uses leased telephone lines where transmissions do not require dialing a telephone number.
- RF: Radio Frequency.
- RSC: Remote Site Controller.
- Remote Site Controller: The component of a remote irrigation control system that performs the actuation of water delivery at the remote site.
- RIC: Remote Irrigation Control.
- Remote Irrigation Control: The control of an irrigation system at a central location distant from the actual irrigation site.
- SCADA: Supervisory Control and Data Acquisition.
- Sensor based programming: refers to the ability of the system to allow specification of custom actions to be executed in response to selected sensor readings, e.g., cancel irrigation at this site if the wind speed exceeds 25 mph.
- Signal bandwidth: the range of frequencies of a signal whose components have significant values for information transfer.
- Simplex system: a communication system in which transmission is possible in one direction only.
- SMRS: see Specialized Mobile Radio System.
- Soil model based adjustments: includes soil type, compaction, infiltration rate and other factors of a soil model provided by the system to characterize the water demands of the remote stations.
- Specialized Mobile Radio System: a conventional or trunked radio system owned by an entrepreneur who sells service on the system to subscribers.
- Station: a point at which water delivery is actuated by a solenoid, electromagnetic valve, etc.
- Station "on time": the start time and duration of water delivery at a station, e.g., thirty minutes starting at 10 A.M.
- Supervisory Control and Data Acquisition system: A type of remote control system to monitor the delivery of oil, gas, water, electric power and other commodities requiring distribution systems spread over a large geographical area.

- Station "on time": the start time and duration of water delivery at a station, e.g., thirty minutes starting at 10 A.M.

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- Synchronous transmission: a data transmission scheme where a common clock is established between both ends to transmit blocks of characters.
- Time based system: one in which the amount of water to be delivered is expressed in terms of duration of water delivery.
- Time based programming: means that water delivery is specified in terms of time units.
- Time-Division Multiplexing: a multiplexing method in which use of the communication line is allotted in time slices.
- Time driven system: one in which the adjustments of water delivery are expressed in terms of duration of water delivery.
- Transmission trunking: a trunked-radio channel assignment scheme where channels are assigned for the duration of a single transmission.
- Trunked radio: a transmission method that utilizes a bank of radio frequencies to allocate connections dynamically when subscribers make calls in a manner similar to the radio portion of cellular telephone service.
- Twisted pair cable: a cable formed by pairs of wire twisted so as to minimize noise from adjacent wire pairs.
- UHF radio: Ultra High Frequency radio, a radio system using frequencies in the 300 Mhz to 3000 Mhz range.
- VHF radio: Very High Frequency radio, a radio system using frequencies in the 30 Mhz to 300 Mhz range.
- Volume based system: one in which the amount of water to be delivered is expressed in terms of volume.
- Volume based programming: means that water delivery is expressed in terms of volume units. Volume based programming requires the use of flowmeters.
- Volume driven system: one in which the adjustments of water delivery are expressed in terms of volume.
- VBI data: Vertical Blanking Interval data.
- VSAT: Very Small Aperture Terminal.
- Water budgeting: the adjustment of a water delivery specification by a percent factor of the original setting.

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